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Petrophysical Characterization Of Reservoir And Oil Properties As A Tool For Choosing Optimal Enhanced Oil Recovery Methods: Case Study Of Dawson Bay Formation, Divide County, North Dakota, United States

Kayode James Olatunji

PETROPHYSICAL CHARACTERIZATION OF RESERVOIR AND OIL PROPERTIES AS A TOOL FOR CHOOSING OPTIMAL ENHANCED OIL RECOVERY METHODS: CASE STUDY OF DAWSON BAY FORMATION, DIVIDE COUNTY, NORTH DAKOTA, UNITED STATES

by

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Date

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Title	Petrophysical Characterization of Reservoir and Oil Properties As A Tool For Choosing Optimal Enhanced Oil Recovery Methods: Case Study Of Dawson Bay Formation, Divide County, North Dakota, United States
Department	Geology and Geological Engineering
Degree	Doctor of Philosophy

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April 2019

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ABSTRACT

In unconventional reservoirs, i.e., shaly or tight sand formations, with low porosity and very low permeability, the oil recovery factor is low hence enhanced oil recovery is important. In the conventional reservoirs, once the primary and secondary stages of recovery are exhausted, about two-thirds of the original oil in place is left behind. Enhanced Oil Recovery aims to recover the remaining oil (Green and Wilhite, 1998). These makes the enhanced oil recovery to be of great importance. Efforts are always in place to see how the system can be improved.

The study was carried out to describe the overview of rock types, depositional environment and diagenetic history of the Dawson Bay Formation, and overview of structural geology of the Dolphin Field by studying the Well logs and Cores from the drilled wells, thin sections and using computer softwares i.e. Neuralog, Petra, Surfer. The petrophysical properties of the formation in the field i.e., rock type, porosity, average permeability, oil saturation, production depth, net thickness, temperature and Oil properties, i.e., API gravity, viscosity, oil composition were determined in the laboratory by experiments including Nuclear Magnetic Resonance (NMR) and careful observations of the well logs, and well logs processing using Neuralog, Petra and Artificial Neural network of Matlab. The validity of Screening Criteria by Taber et al. (1997) which recommends Enhanced Oil Recovery Method(s) for formations based on the petrophysical properties for Dawson Bay Formation in Divide County, North Dakota and the optimal method of Enhanced Oil Recovery for the Dawson Bay Formation in Divide County, North Dakota which has its own distinct petrophysical properties and oil properties at laboratory scale at laboratory scale was investigated by conducting Surfactant and brine concentrations spontaneous imbibition experiments, Carbon Dioxide flooding tests, and Carbon Dioxide 'Huff n Puff' simulation tests using Computer Modelling Group (CMG) STARS software.

The result of the study shows that the reservoir rock, predominantly dolomite, slightly limestone, thickens from about 10 ft to about 100 ft. It's thick at the mid-eastern part of the field and thins sideways. This may likely suggest the topography of the marine environment where the limestone was deposited before it was characterized by diagenesis for hydrocarbon accumulation. The oil producing wells are on Nesson Anticline, the reservoir trap has a structural element. Since no clear closure was seen on the structure of the field, reservoir trap may be attributed to halite plugs in the dolomite rock, making it more stratigraphic than structural. The values of the petrophysical properties of the formation obtained from log analysis deviate from values from core analysis. The correlation value was also too low for a reliable relationship. The correlational coefficient for depth 9917 to 9932 ft with 0.5 ft incremental for Well 12071 is about -0.1932, which shows a poor relationship. Artificial Neutral Network (ANN) was used to establish the relationship which can be used to predict the actual petrophysical properties of the formation in other wells. The EOR screening method from Taber et al. (1997) is to a good extent applicable to the Dawson Bay Formation, Dolphin Field. Surfactant flooding and CO_2-EOR methods are applicable to the formation based on experimental results and CO_2 numerical simulation. The brine, surfactant and CO_2 flooding will improve oil recovery from the formation though in varying degrees. The surfactant gave the highest yield of all from experimental results. The prevailing economics, cost of surface and injection plants, environmental among other considerations will influence the method to be used eventually at a time of execution of EOR operation.

1. INTRODUCTION

1.1 Background/Brief Description of the Nature of the Problem or Study.

In unconventional reservoirs, i.e., shaly or tight sand formations, with low porosity and very low permeability, the oil recovery factor is low hence enhanced oil recovery is important. In the conventional reservoirs, once the primary and secondary stages of recovery are exhausted, about two-thirds of the original oil in place is left behind. Enhanced Oil Recovery aims to recover the remaining oil (Green and Wilhite, 1998).

Wang et al. (2012) studied the enhanced oil recovery processes using an optimal surfactant formulation at reservoir conditions for tight Bakken formation. The results show good oil recoveries of 6.8% to 25.4% using surfactant solutions.

Sorensen et al., (2009) conducted a CO_2 huff ‘n’ puff (HnP) test was conducted on a well that is currently producing oil from the Mission Canyon Formation at a depth of approximately 8050 ft in the Northwest McGregor oil field in Williams County, North Dakota. The percentage of oil in the produced fluid, commonly referred to as the “oil cut,” also more than doubled, going from 2.8% to 6%.

Constant Composition Experiment tests conducted on samples from Montney tight oil play in Western Canadian sedimentary basin using a Pressure-Volume-Temperature (PVT) cell and visualization test revealed that CO_2 can dissolve significantly in the oil and swell it causing more oil recovery (Habibi et al., 2017). Hydraulic fracturing and horizontal drilling have greatly raised volume of oil production from unconventional reserves in the last decade (Christensen et al., 2001, Hawthorne et al., 2013). The rate of oil production has been found to be affected by properties of the reservoir like permeability, wettability, API of oil, initial oil saturation, operational parameters. Song and Yang (2013) conducted laboratory experiments on Bakken Formation of Southern Saskatchewan, they reported that higher oil recovery factor was obtained from water flooding more than immiscible CO_2 'HnP' flooding, and both the miscible and near miscible CO_2 'HnP' processes lead to higher recovery than immiscible CO_2 'HnP' process. They also found out that the optimum injection pressure of CO_2 'HnP' can be set at minimum miscible CO_2 and crude oil and soaking time influences oil recovery. CO_2 geological sequestration (CGS) in depleted or high-water-cut oil reservoirs is a viable option for reducing anthropogenic CO_2 emissions and enhancing oil recovery (Yu et al., 2015)

1.2 Study Area: Dawson Bay Formation, Dolphin Field, Divide County

Dawson Bay Formation underlies portion of the Williston Basin in parts of Montana, Sakatchewan, Alberta, South Dakota and North Dakota. Dolphin Field is located in Divide County in northwestern North Dakota, United States. Fig. 1 illustrates the stratigraphic column of Williston Basin and Total Petroleum system in North Dakota.

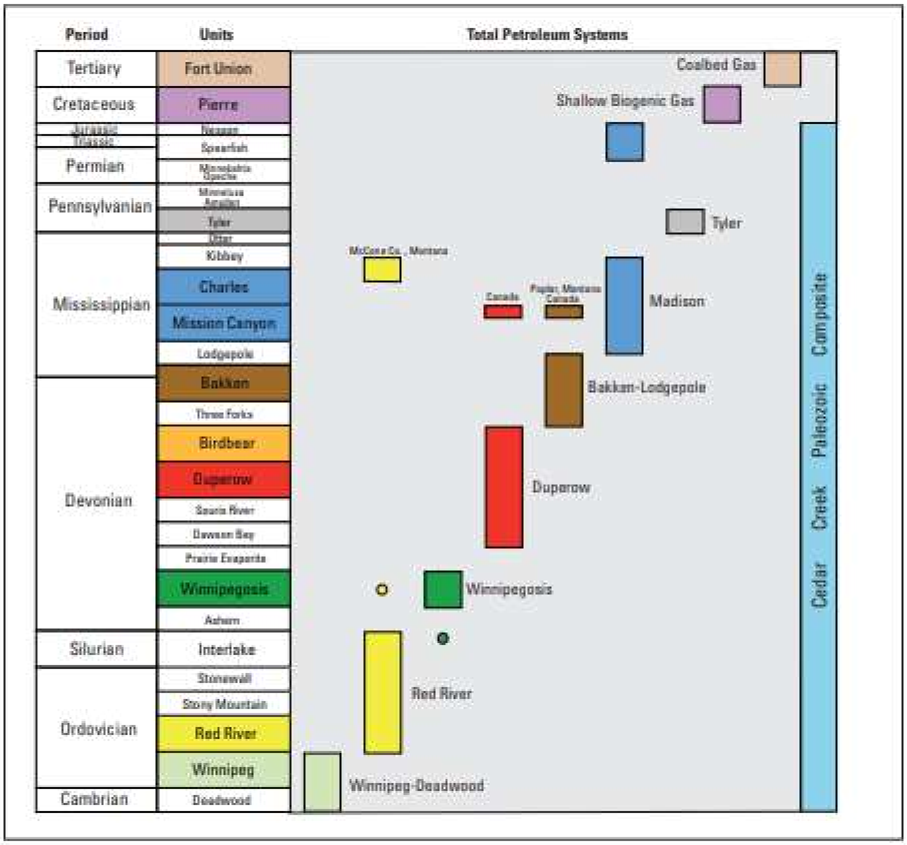


Fig. 1. Stratigraphic column of Williston Basin in North Dakota and associated its Total Petroleum System (TPS). Colored system indicate oil in an assessment unit, in which there are some uncertainty as to its origin. Colored boxes in the unit column indicates formations which are thought to contain source rocks for the TPS (USGS, 2010).

1.3 Objectives of the Study

The main objective of the study is to recommend the optimal Enhanced Oil Recovery Method for Dawson Bay Formation in Divide County.

This study seeks to answers the following questions:

What is the description of overview of rock types, depositional environment and diagenetic history of the formation?

What is the description of overview of structural geology of Dawson Bay Formation, Divide County, in North Dakota?

What is the validity of Screening Criteria by Taber et al. (1997) which recommends Enhanced Oil Recovery Method(s) for formations based on petrophysical properties, i.e., rock type, porosity, average permeability, oil saturation, production depth, net thickness, temperature and Oil properties, i.e., API gravity, viscosity, oil composition for Dawson Bay Formation in Divide County, North Dakota at laboratory scale?

What is the optimal method of Enhanced Oil Recovery for the Dawson Bay Formation in Divide County, North Dakota which has its own distinct petrophysical properties and oil properties at laboratory scale?

1.4 Hypotheses

The optimal method will be dependent on petrophysical properties of the Formation and properties of the oil from the formation.

The brine, surfactant and CO_2 flooding will improve oil recovery from the formation though in varying degrees at laboratory scale.

Testing of the Validity of Screening Criteria by Taber et al. (1999) for the Dawson Bay Formation of Dolphin field, Divide County at laboratory scale will help in its applicability for other reservoirs in the future.

The selected EOR processes will help to keep the oil flowing to wells from Dawson Bay Formation.

2.0 LITERATURE REVIEW

2.1 Overview of Geology of Dawson Bay Formation

Fig. 2. below shows Williston Basin on map of North Dakota, and Canada. It stretches across North Dakota, South Dakota, Montana in United States, Alberta, Saskatchewan and Manitoba (Peterson and MacCary, 1987). It is an intracratonic basin.

Fig. 2. Map of area coverage of Williston Basin

Source: Modified from Worsley and Fuzesy (1978).

The Williston Basin is part of the western North American Paleozoic craton (Peterson and MacCary, 1987).

Devonian Rocks.

In the central part of the Williston Basin, the total thickness of the Middle and Upper Devonian beds is greater than 2,000 ft. Uniform thinning of the beds occurs southward across Montana toward the Central Montana Uplift and along the crest of the Cedar Creek Anticline. These two paleostructures experienced marked structural growth during the Devonian Period (Peterson & MacCary, 1987). The Devonian Period deposition is made up of a cyclic sequence of shallow water fossiliferous carbonates, shaly carbonates, shales, and evaporates. The initial deposits of the Devonian seaway are red dolomite, siltstones, and shale beds. These make up the Ashern Formation, that grades upwards into the Winnipegosis, it's a reef-and mound-bearing carbonate. The Middle Devonian Prairie Formation lies on the Winnipegosis, which is made up of a lower unit of anhydrite, dolomite, thin-shale, and halite beds and an upper halite interval that consists of interbedded red shales. The Dawson Bay Formation lies on the Prairie Formation. The final episode of Middle Devonian deposition is the Dawson Bay, which contains a single carbonate-evaporite cycle (Peterson & MacCary, 1987). The Upper Devonian rocks were deposited at the time of the maximum transgression of the Devonian seaway. They are made up of several cycles of carbonate-evaporite and fine clastic beds. The first of the Upper Devonian units is the Souris River Formation; it consists of several depositional cycles of upward grading clastics into dolomite or limestones capped by anhydrites. The Duperow Formation, a cyclical carbonate-evaporite sequence overlies the Souris River Formation (Peterson & MacCary, 1987).

The Duperow Formation lies below the Birdbear Formation, which is the final carbonate-evaporite cycle of the Devonian. It's four main depositional environments are subtidal, intertidal, lagoonal, and supratidal. The contact between the Birdbear Formation and the overlying Three Forks Formation is conformable with localized erosion (Peterson & MacCary, 1987). The lithology of the Birdbear is a dolostone which is overlaid by sucrosic dolomite and it has uniform lithologic character (Sandberg, 1965). The Three Forks Formation is Upper Devonian and it conformably overlies the Birdbear Formation and it unconformably underlies the Bakken Formation. Its average thickness is 150 feet and a maximum thickness of 250 feet in North Dakota (Webster, 1984).

Lane (1959) divided the Dawson Bay Formation into six members, the designation in ascending order were from DBI to DB6 (Fig. 3).

<table>
<tr><td rowspan="9">MANITOBA GROUP</td><td>BAILLE 1953</td><td>WALKER 1957</td><td colspan="2">LANE 1959</td><td colspan="2">DUNN 1982 a, b</td><td colspan="2">BANNATYNE 1975- Manitoba</td></tr>
<tr><td rowspan="2">UN-NAMED</td><td>SOURIS RIVER FM.</td><td colspan="2">SOURIS RIVER FM.</td><td colspan="2">SOURIS RIVER FM.</td><td colspan="2">SOURIS RIVER FM.</td></tr>
<tr><td>FIRST RED BED</td><td colspan="2">FIRST RED BED</td><td colspan="2">FIRST RED BED</td><td colspan="2">FIRST RED BED</td></tr>
<tr><td rowspan="6">DAWSON BAY FM</td><td rowspan="5">DAWSON BAY FM</td><td>HUBBARD EVAP.</td><td>DB 6’</td><td colspan="2">HUBBARD EVAP.</td><td rowspan="5">DAWSON BAY FM.</td><td rowspan="2">UNIT D</td></tr>
<tr><td rowspan="4">DAWSON BAY FM.</td><td>DB 5’</td><td rowspan="4">DAWSON BAY FM.</td><td rowspan="2">NEELY’</td></tr>
<tr><td>DB 4’</td><td>UNIT C</td></tr>
<tr><td>DB 3’</td><td rowspan="2">BURR’</td><td rowspan="2">UNIT B</td></tr>
<tr><td>DB 2’</td></tr>
<tr><td>SECOND RED BED</td><td>SECOND RED BED</td><td>DB 1’</td><td colspan="2">SECOND RED BED’</td><td>SECOND RED BED'</td><td>UNIT A</td></tr>
<tr><td rowspan="2">UPPER ELK POINT GROUP</td><td colspan="6">PRAIRE EVAPORITE</td><td colspan="2" rowspan="2"></td></tr>
<tr><td colspan="6">WINNIPEGOSIS FM.</td></tr>
</table>

‘- MEMBER

Fig. 3. Stratigraphic nomenclature of the Middle Devonian in Saskatchewan and Manitoba (after Dunn, 1982)

The Dawson Bay Formation was defined by Baillie (1953) as being the lowest sequence of strata in the Middle Devonian Manitoba Group (Figure 3). The Manitoba Group has repetitive sequences of shales and argillaceous limestones which grade upward into lighter colored limestones which in some places are reef forming (Baillie, 1953). Evaporites, made up of both anhydrite and halite, commonly mark the upper boundary of the cycles.

The sediments of the Middle and Upper Devonian are commonly cyclical in nature and they are of a "restricted" nature. Each evaporitic cycle usually begins with green and red shales at the base, then graded upwards into an argillaceous carbonate, which is followed by fossiliferous limestone. The upper beds commonly include a stromatoporoid rich zone, capped by an evaporitic sequence.

The rocks of the Dawson Bay Formation lie conformably over the rocks of the Elk Point Group (Lane, 1959). This group forms a similar evaporitic cycle, with the basal shale unit (Ashern Formation), a carbonate unit (Winnipegosis Formation), and an evaporitic unit (Prairie Evaporite Formation). The Dawson Bay Formation represents a complete cycle of sedimentation within a single stratigraphic unit. The overlying formations of the Souris River, Duperow, and Birdbear, ranging from Middle to Upper Devonian in age, also have sedimentation patterns like that of the Dawson Bay Formation. The pronounced cyclicity of these Devonian units might have been due to minor eustatic or tectonic adjustments (Ahlstrom, 1992).

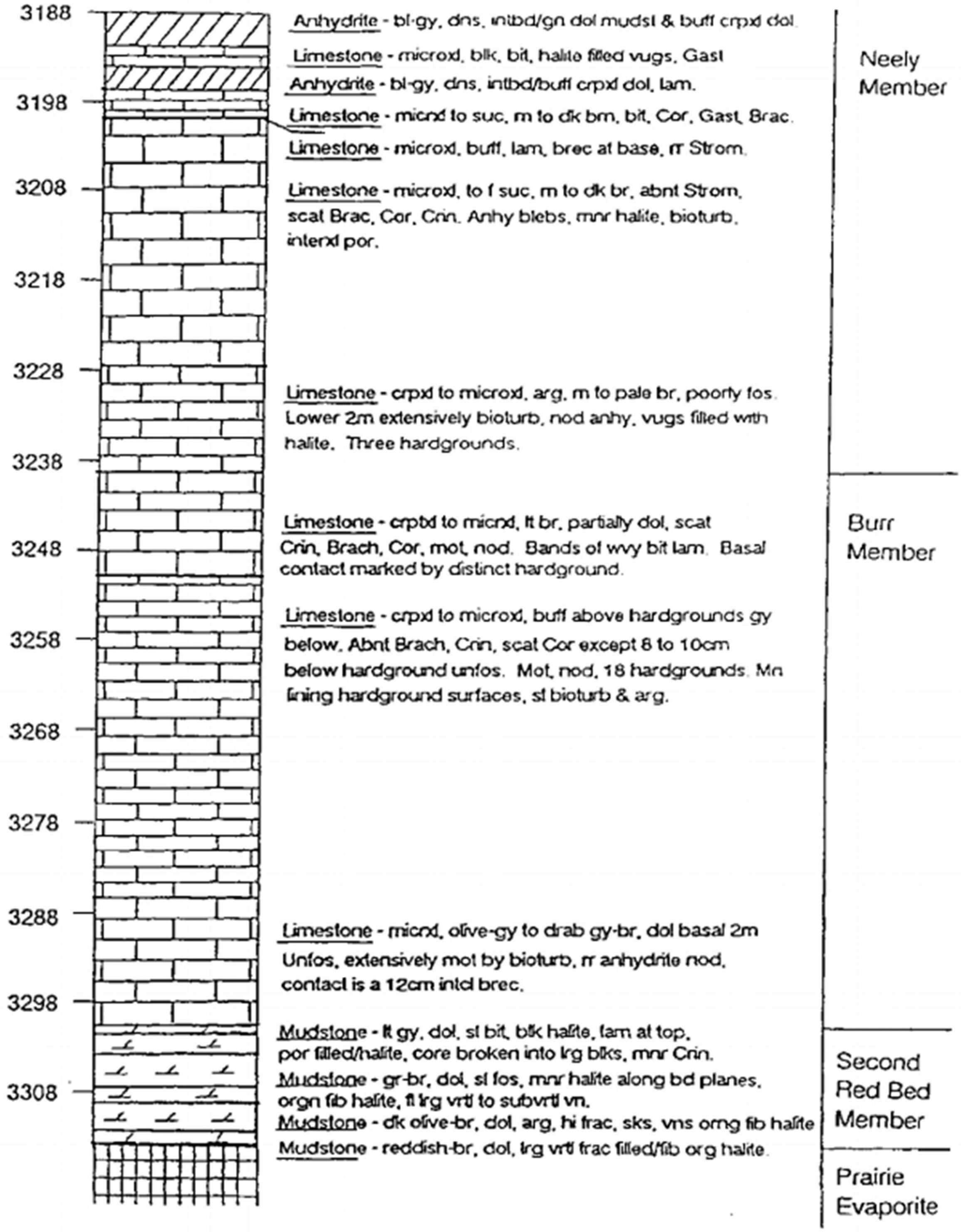
The classification scheme used throughout the study for carbonate rocks is that of Dunham (1962), which is based upon depositional textures. The porosity was described using the terminology of Choquette and Pray (1970). The terminology used to describe the quartz textures is that of Wilson (1966). The classification of the anhydrite textures used in this study is that of Maiklem et al. (1969).

Bannatyne in 1975 recognized four correlatable lithologic boundaries in the type section in Manitoba, which are contrary to boundaries set by Lane. Bannatyne's (1975) divisions can be identified in rocks from Saskatchewan, except the one Bannatyne called unit C (this is an argillaceous unit). Its character is lost in the west where carbonates are the dominant minerals.

Dunn (1982) revised the stratigraphic terms for the members within the Dawson Bay Formation as shown in Figure 5. He split the Dawson Bay Formation into four members which are, in ascending order: Second Red Bed Member, Burr Member, Neely Member and the Hubbard Evaporite Member. Dunn's stratigraphic nomenclature subdivisions have the widest regional application and connect the Dawson Bay Formation in the subsurface of northwestern Saskatchewan with the southeastern portion of the province and the outcrop belt of western Manitoba (Figure 3).

Figure 4 summarizes the stratigraphy of the Dawson Bay Formation, and it was taken from the well 16-21-34-27W2 (Canada).

16-21-34-27W2


3188
3198
3208
3218
3228
3238
3248
3258
3268
3278
3288
3298
3308
Anhydrite - bl-gy, dns, intbd/gn dol mudst & buff crpxl dol.
Limestone - microxl, blk, bit, halite filled vugs, Gast
Anhydrite - bl-gy, dns, intbd/buff crpxl dol, lam.
Limestone - micrxl to suc, m to dk brn, bit, Cor, Gast, Brac.
Limestone - microxl, buff, lam, brec at base, rr Strom.
Limestone - microxl, to f suc, m to dk br, abnt Strom, scat Brac, Cor, Crin. Anhy blebs, mnr halite, bioturb, interxl por.
Limestone - crpxl to microxl, arg, m to pale br, poorly fos. Lower 2m extensively bioturb, nod anhy, vugs filled with halite. Three hardgrounds.
Limestone - crptxl to micrxl, lt br, partially dol, scat Crin, Brach, Cor, mot, nod. Bands of wvy bit lam. Basal contact marked by distinct hardground.
Limestone - crpxl to microxl, buff above hardgrounds gy below. Abnt Brach, Crin, scat Cor except 8 to 10cm below hardground unfos. Mot, nod, 18 hardgrounds. Mn lining hardground surfaces, sl bioturb & arg.
Limestone - micrxl, olive-gy to drab gy-br, dol basal 2m Unfos, extensively mot by bioturb, rr anhydrite nod, contact is a 12cm intcl brec.
Mudstone - lt gy, dol, sl bit, blk halite, lam at top, por filled/halite, core broken into lrg blks, mnr Crin.
Mudstone - gr-br, dol, sl fos, mnr halite along bd planes, orgn fib halite, fl lrg vrtl to subvrtl vn.
Mudstone - dk olive-br, dol, arg, hi frac, sks, vns orng fib halite
Mudstone - reddish-br, dol, lrg vrtl frac filled/fib org halite.
Neely Member
Burr Member
Second Red Bed Member
Prairie Evaporite

Abbreviations

abnt	Abundant	lwr	Lower
Alg	Algal	m	Medium
ang	Angular	mat'l	Material
anhy	Anhydrite	microxl(micxl)	Microcrystalline
arg	Argillaceous	micsuc	Microsucrosic
bd	Bedded	mod	Moderately
bioturb	Bioturbated	mot	Mottled
bit	Bituminous	mnr	Minor
bl	Blue (ish)	mudst	Mudstone
blk (bloc)	Blocky	nod	Nodule
bk	Black	occ	Occasional
bnd	Banded	org	Organics
Brac	Brachiopod	orgn	Orange
brec	Brecciated	por	Porosity
br	Brown	pyr	Pyrite
bur	Burrowed	rr	Rare
calc	Calcite	scat	Scattered
carb	Carbonaceous	skel	Skeletal
cmt	Cement	sks	Slickensided
conc	Concentrated	sl (sli)	Slightly
Cor	Coral	strg	Stringers
Crin	Crinoid	Strom	Stromatoporoid
crpxl	Cryptocrystalline	suc	Sucrosic
disol'n	Disolution	thn	Thin
dk	Dark (er)	thru	Throughout
dns	Dense	tr	Trace
dol	Dolomite (ized)	trnsl	Translucent
f	Fine (ly)	trnsp	Transparent
fib	Fibrous	unfos	Unfossiliferous
fis	Fissile	v	Very
fl	Fill (ed)	vn	Vein
fos	Fossiliferous	vrtl	Vertical
frac	Fractured	/	With
fri	Friable	w	Well
g	Good	wh	White (ish)
Gast	Gastropod	wvy	Wavy
grdg	Graded	xl	Crystal (line)
gn	Green		
gy	Grey		
hardgnd	Hardground		
hi	Highly		
hrtl	Horizontal		
inc	Increased		
indst	Indistinct		
intbd	Interbedded		
intcl	Intraclasts		
interxl	Intercrystalline		
intmixed	Intermixed		
lam	Laminated		
lchd	Leached		
lrg	Large		
lt	Light		

Fig. 4. Stratigraphic sequence showing the general lithology of the Dawson Bay Formation (Source: Ahlstrom, 1992)

Infilling by halite is the single most important event which affect the porosity in the Dawson Bay Formation. Anhydrite cements also locally reduce the porosity. The early anhydrite and halite likely originated from the fluids contemporaneous with the sabkha environments, whereas the halite that infills fractures probably was derived from subsurface brines (Ahlstrom, 1992).

The Dawson Bay Formation is generally 30 to 40 m thick. It thins to the west of Saskatchewan, and thickens to about 52 m in Manitoba. Over part of eastern Saskatchewan an increased thickness is attributed to the local development of a halite bed at the top of the formation (Dunn, 1982). The Devonian System of north-central North Dakota is represented by Middle and Upper Devonian rocks. The Middle Devonian rocks include in ascending order the Winnipegosis, Prairie, Dawson Bay and part of the Souris River. The Upper Devonian is represented by the upper portion of the Souris River, the Duperow, Birdbear, and Three Forks Formations. The total Devonian thickness in the northcentral part of the state is about 1400 feet. In this (northcentral part) area and in the rest of the Williston Basin the Devonian consists predominantly of carbonate rocks, with the fine grained clastics of limestone, sucrosic dolomite and siltstones of the Three Forks and evaporites of the Prairie Formation the only exceptions (Anderson and Hunt, 2010).

Dawson Bay Formation.

The Dawson Bay Formation was named by Baillie (1953, p. 26) from exposures he found along the shores of Dawson Bay at the northern end of Lake Winnipegosis in Manitoba. Baillie (1953, 1955) correlated the formation from the outcrop area into the subsurface of the Williston Basin. He placed the Dawson Bay Formation and the overlying unnamed beds that are approximately equivalent to the Souris River Formation of this report in the Manitoba group. This grouping is not recommended for the part of the Williston Basin located in the United States because the Dawson Bay and Souris River Formations are readily separable, and the Souris River has a greater lithological similarity with the overlying Upper Devonian rocks (Sandberg and Hammond, 1958). In the Birdbear Well No 1, the Dawson Bay Formation lies between depths of 11,052 and 11,170 feet. The formation varies in thickness between a fraction of a foot to 185 feet and is thickest along the international boundary in northcentral part of North Dakota. The Dawson Bay underlies approximately the same area as the Elk Point Group in the Williston Basin and northeastern Montana but extends slightly beyond the limit of the Winnipegosis Formation. The Dawson Bay Formation does not crop out within the United States. The Dawson Bay Formation was deposited during a single sedimentary cycle which is represented by a definite sequence of beds. The complete sequence, although not everywhere present, is made up of the following units in ascending order: (1) dolomitic siltstone or silty argillaceous dolomite, (2) thin-bedded argillaceous limestone, (3) thick-bedded crystalline limestone or dolomite, (4) anhydrite or anhydritic limestone and dolomite. The formation is divided into two members, readily identifiable on radioactivity well logs, based on this sequence. The lower two units constitute an argillaceous member and the upper two units constitute a carbonate member. The argillaceous member has a thickness of 10-20 feet in central North Dakota and it consists of dolomitic siltstone or silty argillaceous dolomite, which is interbedded with argillaceous limestone and dolomitic shale, and the color is generally light brown or grayish red. The thickness of carbonate member ranges from 100 to 150 feet in central North Dakota and it consists of finely crystalline to micro-crystalline porous dolomite or limestone, anhydritic in the upper part. In some wells, the upper 10-15 feet is bedded anhydrite. The carbonate member ranges from brownish gray or medium dark gray in central North Dakota to light gray or light brownish gray on the margins of the Williston Basin. Near the limit of the Dawson Bay Formation in eastern North Dakota and northeastern Montana, the thickness of the carbonate member decreases and the thickness of the argillaceous member increases, and the over -all thickness of the formation thins slightly. The uniform lithological character of the Dawson Bay Formation helps to easily recognize the unit on lithologic and radioactivity well logs. It is readily differentiated from the overlying Souris River Formation which represents many similar but less complete sedimentary cycles. Because of its lithologic uniformity and slightly variable thickness, the Dawson Bay Formation provides a useful datum for regional subsurface correlation. The Dawson Bay Formation conformably overlies the Elk Point Group, to which it is faunally related, and its age is Middle Devonian (Baillie, 1953, p. 42). The Dawson Bay is conformably overlaid by the Souris River Formation in the central part of the Williston Basin where deposition was probably continuous from Middle to Late Devonian time. The contact between the Dawson Bay and Souris River Formations is disconformable in parts of northeastern Montana, and in some wells the carbonate member was considerably thinned or completely removed by erosion which preceded deposition of the Souris River (Sandberg and Hammond, 1958).

The middle Devonian Dawson Bay carbonate unit is present in the subsurface of North Dakota except where truncated by post-depositional erosion. The carbonate unit thickens from the erosional limit to maximum thickness of 47.5 m (156 ft.) in Renville county (Sandberg and Hammond, 1958).

2.2 Enhanced Oil Recovery Methods and Applications

The Primary Recovery of oil utilizes natural pressure of the reservoir to push crude oil to the surface. It produces about 5-10% of the oil in the reservoir (Udumbasseri, 2018).

Secondary Recovery has to do with injecting pressurized gas and water to drive the residual crude oil and gas left after the primary oil recovery phase to the surface wells. It can extract about an additional 25% to 30% of the oil in the reservoir (Udumbasseri, 2018). Lake et al. (2014) defined Enhanced Oil Recovery as oil recovery done by injecting materials which are not normally present in petroleum reservoirs. They described it as one of the technologies needed to maintain reserves (Lake et al. 2014). They stated that statistics has shown that the conventional ultimate oil recovery, i.e., the percentage of Original Oil in Place produced at the time when further conventional recovery (i.e. primary and secondary recoveries) becomes no more economical is approximately 35%. They said that this implies that if the OOIP in all reservoirs in the US is considered, that will be much higher than targets from exploration or additional drillings.

The success of the EOR process is evaluated by the amount of incremental oil recovered (Lake et al, 2014). EOR is also called Tertiary Recovery. Here, different materials are injected to improve the flow between oil, gas and rock, and to recover crude oil remaining after the primary and secondary oil recovery phases. It allows an additional 20% to 30% of the oil in the reservoir to be extracted (Udumbasseri, 2018).

EOR classification

The processes of the EOR can be grouped into three major categories. The methods are mainly related to the kind of oil remaining to be taken and the characteristics of the reservoir. The methods are:

Chemical: This consists of (1) Surfactant Imbibition or Flooding, (2) Micellar Polymer Flooding, (3) Polymer Flooding (4) Alkaline or Caustic Flooding; Thermal: i.e., (1) Steam Flooding (2) Fire Flooding; Miscible: i.e., (1) Carbon Dioxide Flooding, (2) Nitrogen and Flue Gas Flooding, (3) Enriched Hydrocarbon Gas Flooding. (Udumbasseri, 2018). Lake et al. (2014) categorized EOR into 3 processes, i.e., Chemical, Thermal and Solvent.

EOR-Chemical Flooding

Surfactants exhibit interfacial activities. They are able to adsorb and form layers on rock surfaces. Available evidence suggests that they then change the wettability of the formation to aid enhanced oil recovery (Xu et al., 2015). The mechanism of surfactant EOR mainly includes the decrease in Interfacial Tension (IFT) and moving the reservoir wettability to water wet. The residual oil is immobile after water flooding due to the surface tension between oil and water. In addition, the differential pressure cannot overcome the high capillary pressure to move oil out from pores. The residual oil can be mobile after encountering surfactants. The surfactants can reduce the IFT, thereby decreasing the capillary pressure and allowing water to remove the trapped oil by water pass. By driving the reservoir's wettability to more water wet and lifting the attached oil film from the pore wall, surfactants reduce oil saturation and enhance oil recovery (Negin et al., 2017).

Adibhatla, Mohanty, Gupta et al. carried out a series of studies using anionic and nonionic surfactant to change the wettability of oil-wet carbonate (Adibhatla, Sun and Mohanty, 2005; Adibhatla and Mohanty, 2006; Gupta and Mohanty, 2007; Gupta and Mohanty, 2008). Their studies involved coupling imbibition of aqueous surfactant solutions with gravity drainage. Both anionic and nonionic surfactants gave results showing good potential for increasing oil recovery in a fractured limestone carbonate reservoir at 90°C. In continuation of the series of study, Gupta and Mohanty screened surfactant for wettability alteration in an oil-wet fractured carbonate reservoir (Gupta, Mohan and Mohanty, 2009). Anionic and nonionic surfactants were screened for high temperature (～90°C) and high salinity (～8 wt%) systems containing significant concentrations of magnesium and calcium ions in the study. They added Alkali to keep the brine pH above neutral and reduce adsorption on carbonate surfaces. In their study, the optimal salinity was changed by either changing surfactant concentration or using a mixture of surfactants (Gupta and Mohanty, 2009). Wang et al. (2010) conducted study on flow behavior and imbibition using brine in shale rock. Their results indicate that aqueous imbibition could bring increase to oil recoveries from shales. Likewise, Shuler (2010) suggested that specialized surfactant formulations may be used to recover oil from Bakken shale.

EOR -Thermal Injection.

Thermal Flooding-Steam Stimulation.

The temperature of a reservoir can be increased through Steam Cycling or Stimulation, Steam Drive and in-situ Combustion. Thermal flooding was the leading method in EOR processes especially for viscous or heavy oils. Most of the oil which has been produced by EOR methods to date is produced through thermal processes (Udumbasseri, 2018)

EOR -Gas Injection

Table 1. EOR Natural Gas

	Nitrogen	CO_2	Flue gas
•source	•Produced from air by cryogenic separation •Available from 95-99%	•No natural source •Captured from flue gas of coal power plant	From combustion
•Properties	Inert and non corrosive-no need of corrosion inhibitor Existing injection system may be used Available with <10ppm O_2 No need for biocide	Corrosive-need special corrosion inhibitors /corrosion resistant infra structure Plugging due to asphaltene precipitation CO_2 removal from production is costly Only very slightly miscible with crude	Corrosive SOX and NOX presence O2 to be removed CO2 to be removed which is costly

(Udumbasseri, 2018).

EOR-CO_2 Injection

The conventional CO_2 flooding process (e.g. Continuous CO_2 Flooding or Water Alternating CO_2 (CO_2-WAG) flooding) requires a large volume of CO_2 gas and initial breakthrough restricted their extensive applications (Bellveau et al., 1993). CO_2 'Huff n Puff' (HnP) processes have proven to enhance oil recovery in some tight reservoirs (Haskin and Alston, 1989). The 'HnP' process entails injection of CO_2 into the reservoir at certain pressure, the injection wells are shut in to allow the soaking for a period before the wells are switched to production wells (Song and Yang, 2013).

Todd and Evans (2013) reported that in pilot tests of CO_2 flooding in the Bakken, injection was not a problem. The reservoirs which have complex natural and induced fractures that may lead to early injected gas appearing in producing well, lead to low volumetric sweep efficiency and bypassing of the oil in the matrix system (Sheng, 2015).

The category comparison of EOR processes by driving mechanisms and issues is shown in Table 2 below (Lake et al., 2014).

Table 2. The category comparison of EOR processes.

Process	Recovery mechanism	Issues	Typical recovery (%)	Typical Agent Utilization
Chemical EOR Processes				
Polymer	Volumetric sweep is increased by mobility reduction	Stability, injectivity and high salinity	5	1 Ib polymer per incremental bbl
Surfactant/ polymer (SP)	The same as in polymer but in addition reduces capillary force.	The same as in polymer but also, chemical availability, retention and high salinity.	15	15 to 25 Ib surfactant per incremental bbl.
Alkaline/ polymer	The same as surfactant/polymer with oil solubilization and alteration of wettability.	Same as in SP, plus oil composition.	5	35-45 Ib chemical per incremental bbl
Alkaline/surfactant/ polymer	The same as Surfactant/polymer	Same as SP, also has lower salinity requirements, mineral precipitation	-	-
Thermal EOR Processes				

Steam (drive and stimulation)	It reduces viscosity of oil; vaporization of light ends.	Depth, heat losses, override, pollution	50-65	0.5 bbl of oil is consumed per incremental bbl.
In-situ combustion	Same as steam, in addition cracking	The same as steam, additionally control of combustion.	10-15	10 Mcf air per bbl oil produced.
EM heating	Same as steam, additionally some cracking and distillation.	Propagation of heat	Same as steamdrive	Same as steamdrive
Note: 1 Ib/bbl=2.86 kg/m3, 1Mcf/STB=178 std m^3 gas/std m^3 oil				
Solvent EOR Methods				
Immiscible	Oil viscosity is reduced, oil swelling, solution gas	Override, stability, supply	5-15	10 Mcf solvent per incremental bbl
Miscible	The same as immiscible additionally development of miscible displacement	Same as immiscible	5-10	10 Mcf solvent per incremental bbl.
1 Mcf/STB= 178 SCM solvent/SCM oil				

Source: (Lake et al., 2014).

2.3 Enhanced Oil Recovery in Tight Formations

Experiments carried out on cores from the Bakken in southern Saskatchewan showed that immiscible, miscible, and near miscible CO_2 ‘HnP’ led to higher oil recovery in different proportions, the best at near and miscible CO_2 flooding (Song and Yang, 2013). There have been a number of pilot tests in the Bakken to validate the promising results of experimental and numerical simulations. The CO_2 pilot tests show early breakthrough times and low sweep efficiency. There has not been a significant surfactant pilot test. The pilot tests were reported to be limited in scope and time, and more careful studies with economics were recommended for further pilot tests (Todd and Evans, 2016).

The average recovery factors (RF) are significantly lower in most of the unconventional reservoirs than in the conventional reservoirs. There has been great amount of theoretical studies carried out to improve the recovery from unconventional reservoirs, only few field applications. Eagle Ford has some pilot test projects ongoing. Permian Basin has more EOR projects than any other play in the US, most of them are conducted on reservoirs classified as conventional (Wang et al., 2017).

3.0 METHODS

3.1 Selection of Study Wells

Figs. 5 and 6 show the location of wells in Dolphin Field with available cores in Wilson Laird Core Library located on UND campus, Grand Forks, ND. The maps were produced using ArcMap 10.6.4 software.

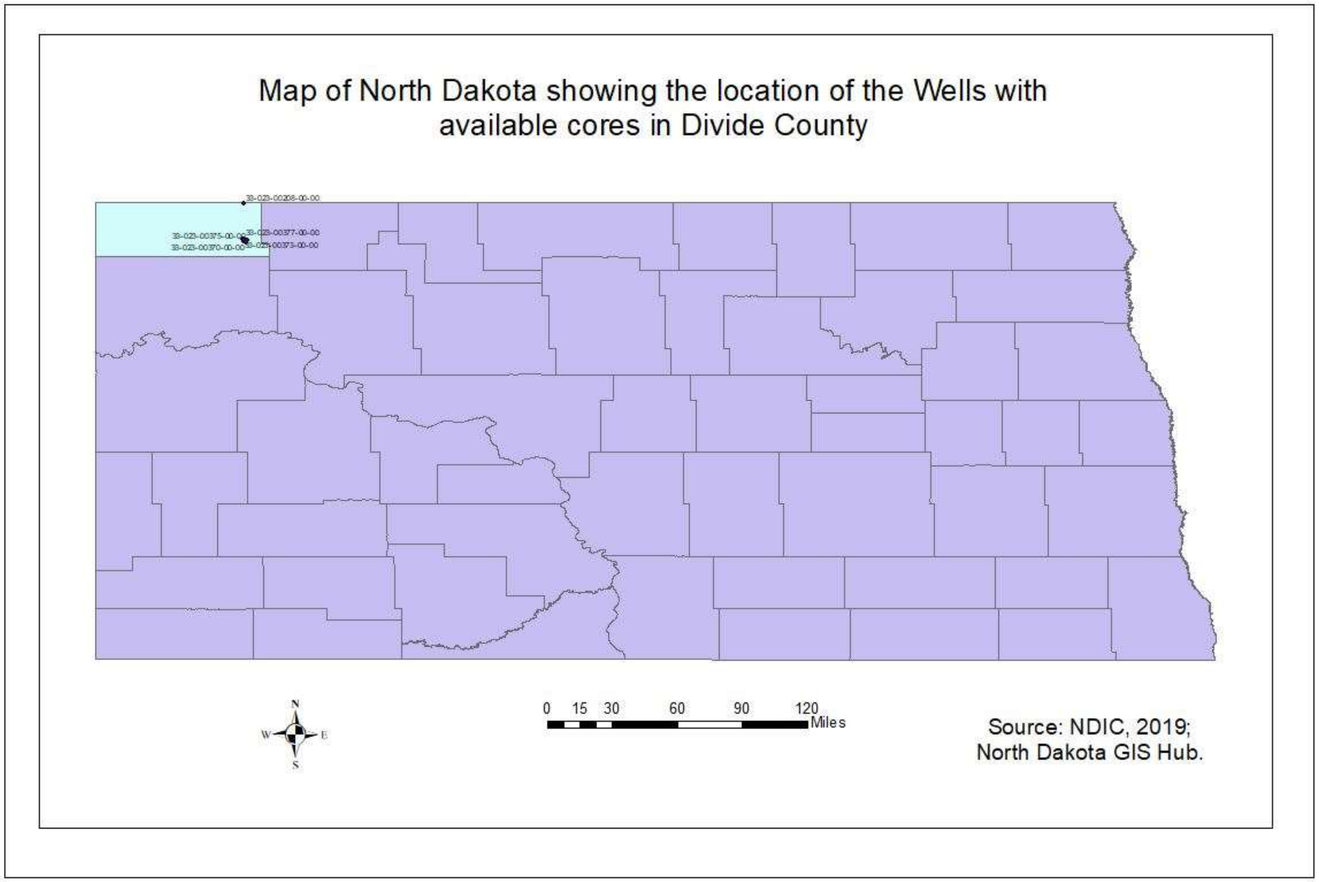


Fig. 5. Map of North Dakota showing the location of the wells with available cores in Divide County.

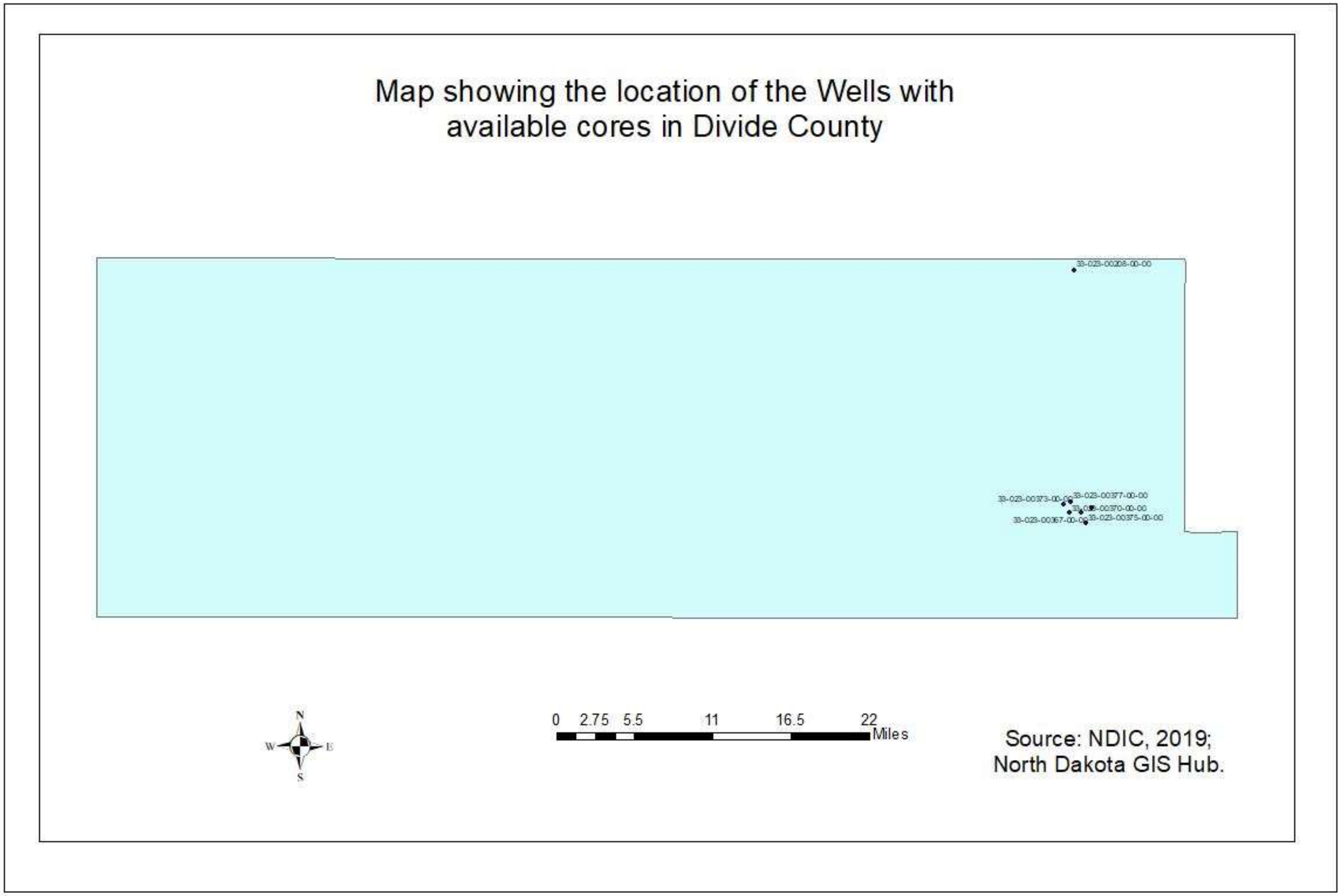


Fig. 6. Map of Divide County showing the location of the wells with available cores.

Table 3 shows the wells with available cores, their status, the range of depth of reservoir rocks, the period and formation the reservoir rock belongs to and the hydrocarbon field. The cores used for the experiment in this study were taken from active wells.

Table 3. Description of the wells of Dawson Bay Formation in Divide County in North Dakota with available cores in Wilson Laird Core library by November 2016.

S/No	**Well-File No**	**Status**	**Depth (feet)**	**Period/Formation/Field**	
1	12071	A/OG	9913-9978	Devonian/Dawson Bay/Dolphin	
2	12085	A/OG	7432-7975	Devonian/Dawson Bay/Dolphin	
3	12086	A/OG	9955-10014	Devonian/Dawson Bay/Dolphin	
4	12114	A/OG	9934-10004	Devonian/Dawson Bay/Dolphin	
5	12149	IA/OG	10023-10086	Devonian/Dawson Bay/Dolphin	
6	12158	DRY/OG	9912-9972	Devonian/Dawson Bay/Dolphin	
7	9303	DRY/OG	8628-8723	Devonian/Dawson Bay/Dolphin	

N.B: A -active; IA -Interim Abandoned; OG -Oil and Gas, DRY -Dry Well, PNA -Plugged and Abandoned.

3.2 Logs Compilation

The Compensated Neutron Density (CND) and Laterolog Deep (LLD) logs of the wells in Dolphin Field which have available cores in the Dawson Bay Formation and are active were downloaded from the website of the North Dakota Geological Survey. The downloaded logs were analogue. They were digitized using Neuralog software. Surfer software was used to draw the contour and isopach maps and cross-sections. Petra software was also used for drawing cross-sections along and across the Dawson Bay Formation in Dolphin field. The maps and cross-sections are shown in chapter four.

3.3 Core Descriptions

Core-log matching

The core to log matching was carried out by observing the cores and the Compensated Neutron Density (CND) logs. In some cases, there are offset between the two and correction needs to be applied. The table showing the cores descriptions is shown in chapter four of this report.

3.4 Lithofacies Description

The result of description of lithofacies of the Dawson Bay Formation in Dolphin Field was obtained using the information from the core description, logs and reviewed literature. The thin section slides of rocks at depths of the wells in the Dawson Bay Formation, Dolphin Field were obtained from the Wilson Laird Core Library of the North Dakota Geological Survey. They were observed in the library using a petrographic microscope, Olympus U-TVIX-2 Japan with software SPOT Insight 2 megasample. The microscope was also used to take the photographs. They were studied to observe the texture of the reservoir rocks in the Dawson Bay Formation and the nature and distribution of the porosities. The result of the lithofacies study is in chapter four of this report.

3.5 Description of Petrophysical Properties of Dawson Bay Formation, Dolphin Field, Divide County

Using Cores and Logs

The petrophysical properties of the formation were determined using calculations from digitized logs using Petra software. The petrophysical properties of the cores were obtained from the well file of the North Dakota Industrial Commission, and results of the experiments carried out in the Enhanced Oil Recovery (EOR) Laboratory, Leonard Hall on cores. The cores for the imbibition and flooding experiments were obtained from Wilson Laird Core Laboratory, UND. The 1-inch diameter cores were obtained from the core slabs collected from the core library. The slabs were drilled using a Rockwell, 20-inch Drill Press core drill at the Sampling Laboratory in Leonard Hall of University of North Dakota, Grand Forks.

3.5.1 Oil Saturation

The sample of crude oil from the Dawson Bay Formation was obtained from Continental Resources LLC, operating on Dolphin Field. The oil was used to saturate the cores for imbibition experiment and core flooding using Hassler cell procedure in the EOR Laboratory. The saturation values are shown in chapter four of this report.

3.5.2 Porosity

The porosity of core samples used were carried out in the EOR Laboratory, Leonard, UND using the method of the porosity measurement by imbibition/weight difference using core samples (Wang et al., 2011). The crude oil and brine from the formation were used as saturating fluids at different times. Nuclear Magnetic Resonance (NMR) porosity measurement were carried out in the Material Characterization Laboratory of the College of Engineering and Mines, UND on the cores used for the experiments. After the samples had been fully saturated, pore-size distributions were obtained using NMR T2 analysis in Oxford Instruments Geospec 2 core analyzer which is coupled with Green Imaging Technologies software 7.5.0. The procedures are shown in the appendix of this report. The result is shown in chapter four of this report.

3.5.3 Average Permeability

The method of Measurement of Effective Permeability using ISCO Pump was used in the EOR Laboratory, Leonard, UND to determine the Effective Permeability of the cores used for the experiment. The procedure is in the appendix of this report. The result is shown in chapter four.

3.5.4 Net Thickness

The thickness of the formation (feet) in each of the wells is estimated using the data which were available on the North Dakota Industrial Commission's website, i.e., CND logs and well files.

3.5.5 Formation Depth

The depths of the formation at different well points in the field was determined from well files on the NDIC website.

3.5.6 Formation lithology

The lithology of the formation was determined from core description carried out in the Wilson Laird Core library on the UND campus, the logs downloaded from the North Dakota Industrial Commission (NDIC) website in corroboration with data from well files on the NDIC website.

3.5.7 Formation Temperature

The information about formation temperature in respective wells was obtained from well files on the NDIC website.

3.5.8 Review of Petrophysical Properties

The data of petrophysical properties of the cores were compared with the corresponding data at depths calculated using logs. The CND and GR and LLD logs from the website of NDIC were downloaded and digitized using Neuralog software. The total porosity and fluid saturations of intervals in the reservoir rocks of the Dawson Bay Formation of Dolphin Field in Divide County, ND were calculated using Petra software.

The results obtained were compared with the values obtained from analysis of core plugs from respective depths in the NDIC well files and EOR Laboratory in UND. Data on lithology and petrophysical properties on the NDIC website were also investigated and employed. Cross plots of Bulk density against Neutron density was also used for some depths, the results obtained were not comparable. The use of Artificial Neural Network (ANN) on conventional logs of Neutron porosity, Density porosity and Bulk density was employed, and the result yielded a relationship which can be used to predict the porosity for other parts of the well without core values. The use of ANN involved multiple iterations until a reliable result is obtained. The results are shown in chapter four.

3.6 Oil properties

3.6.1 Viscosity

The viscosity of the oil was determined at the EOR Laboratory of UND using the Brookfield DV-E Viscometer. The procedure is described in the appendix of this report. The crude oil obtained from the Dawson Bay Formation, supplied by Continental Resources LLC, operating on Dolphin Field was used. The result is shown in chapter four.

3.6.2 API Gravity

The specific gravity of the oil from the Dawson Bay Formation was determined at room temperature of 70-degrees Fahrenheit in the EOR Laboratory, UND using a hydrometer with model/item No. 265726 of DURAC Hydrometer Set. The temperature of the oil was measured using the thermometer Total Immersion Enviro-Safe model number N53724 manufactured by H-B USA. The procedure is in the appendix of this report. The result was used to calculate the API gravity of the crude oil using the formula:

$$\text{API Gravity} = \frac{141.5}{Specific\ Gravity} - 131.5$$

The result is shown in chapter four of this report.

3.6.3 Oil Composition

Oil Characterization

The data of oil characterization was obtained from the NDIC well files. The result is presented in chapter 4 of this report.

3.7 Cores Sample Preparations for Spontaneous Imbibition and CO_2 Flooding Experiment

The objective of any coring and core preservation program should be to obtain rock that is representative of the formation while minimizing physical alteration of the rock during coring and handling (Skopec, 1994).

3.7.1 Cores Cutting

The drilled cores were cut into lengths in order to have a smooth surface using the machine in the Sampling Laboratory.

3.7.2 Cores Cleaning

Distillation-Extraction (Dean-Stark and Soxhlet) method was used for core cleaning. It is the most commonly used for samples cleaning method. The samples were placed in the Dean-Stark apparatus. Solvents were evaporated and flowed through the core removing the fluids in place. Then they condensed and evaporated again in a continuous closed process. The experiment was carried out in the EOR Laboratory using the Dean-Stark produced by Corrected Systems Inc. California, model no DS-206, S/N 195813. The chiller was produced by VWR.

Procedure:

* About 200mL of a 50%/50% by volume of a toluene/methanol mixture was put in the volumetric flask.

* The volumetric flask and the solvent mixture were placed on the heating mantle.

*   The reflux core chamber was attached to the volumetric flask.

*   This was done for about 48 hours as recommended by Gant et al., (1986) and Cuiec (1975).

Fig. 7 shows the Dean-Stark used for the cleaning. The toluene/methanol ratio used by volume is 1:1.

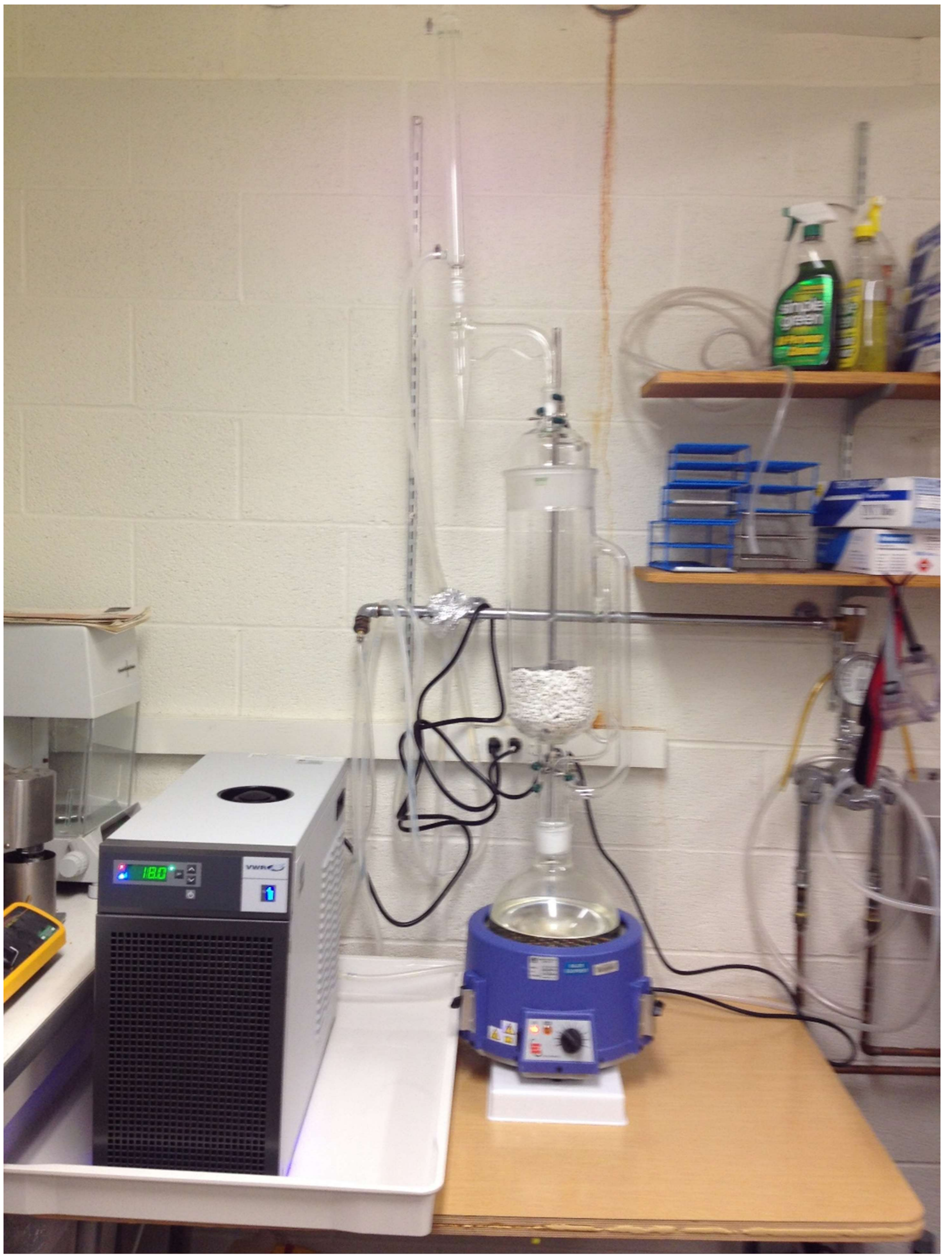


Fig. 7. Photo of Dean-Stark apparatus.

The cut cores were cleaned using toluene and methanol. The toluene is for hydrocarbon cleaning while methanol is for brine cleaning.

3.7.3 Cores Drying

The cleaned cores were dried in an oven, set at a temperature of 105 deg C for 24 hours. The oven was produced by Quincy Lab Inc., it is Model 40 GC Lab Oven

3.7.4 Cores Degasification

The cores were degasified in the EOR Laboratory with the purpose of removing trapped gases in the pore spaces of the cores. This was done by putting the cores in a closed bottle with a vacuum pipe connecting the bottle with a pump extracting air from the cores. This was done for 2 to 3 hours.

3.7.5 Cores Measurements: Dimension and Mass

Table 4 shows the dimension and mass of the core samples used for the experiments.

Table 4. The Dimensions of the Core Samples used for the Experiments.

S/No	Core	Height (mm)	Diameter (mm)	Dry Mass After Air Vacuuming (g)	Imbibing Solution
1.	71-2	50.42	31.858	106.9915	Base brine (4% salinity) +VX12279 @ 0.2%
2.	71-3	50.758	32.008	108.7703	Base Brine (4% salinity) +VX12279 @ 0.2%
3.	85-1	57.306	31.86	117.9938	Base Brine @ 10%
4.	85-4	51.008	31.75	106.2894	Base Brine (10% salinity) + VX12279 @ 0.2%
5.	114-1	50.828	31.768	107.7797	Base Brine (15% salinity) + VX12279@ 0.1%
6.	114-2	49.9	31.75	108.8743	Base Brine (10% salinity) + VX12279 @ 0.1%
7.	149-2	50.11	31.92	108.2288	Base Brine (15% salinity) + VX12279 @0.2%
8.	149-3	50.902	31.966	103.2314	Base Brine (10% salinity) + VX12279@ 0.2%

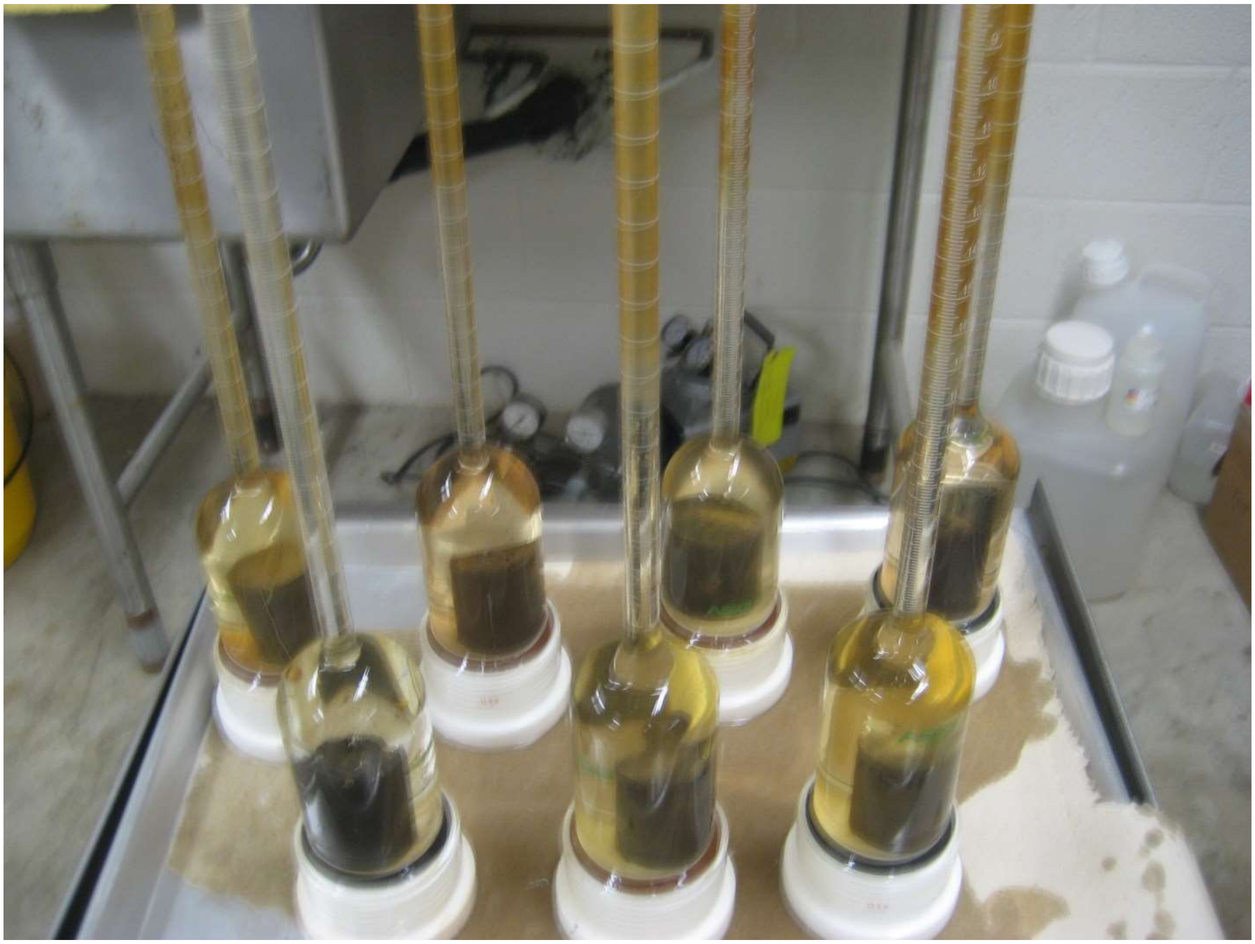


Fig. 8. Cores in the imbibition cells after spontaneous imbibition experiment.

3.8 Enhanced Oil Recovery (EOR) Process Screening Methods.

The selected cores from Active wells were used for experimental investigation. They were tested for Brine, Surfactant and Carbon Dioxide flooding. These were done to determine the amount of the Original Oil in Place (OOIP) in the cores which can be recovered using any of these methods.

3.8.1 Aqueous Liquid Spontaneous Imbibition Laboratory and Simulation Study for Surfactant and Brine stimulations.

Cores Fluid Saturation Using Hassler Cell

The vacuumed cores for oil saturation were weighed, the values obtained were recorded. An ISCO Model 100DX syringe pump which has low flow rate capability was used to saturate the cores with oil. The distilled water was pumped into the ISCO pump first with a flow rate of 500 mL/hr, distilled water was run from a pump into a transfer cylinder with the same flow rate. Crude oil was pumped into the transferred cylinder (The oil occupied the upper part, whereas the water stays in the lower part of the cylinder, due to density difference. The approximate volume of the cylinder is 250cm^3 capacity).

The cores were put in Hassler's cell with an injection pressure of about 130 psi and confining pressure of 700 psi. The pressure changes were recorded.

Spontaneous Imbibition Tests of Brine and Surfactant Formulations on the Cores.

This is useful for recovery of oil especially when the matrix of reservoir rock is partially or strongly oil wet. In the process of spontaneous imbibition, the imbibition cells (Amott Cells) were immersed in a temperature bath, manufactured by Thermo Scientific (Model NESLAB Ex 35) at 115^{o}C (formation temperature). The cells were filled with a volume of aqueous solution of either surfactant, brine, or both in different concentrations, then they were put in a temperature bath at reservoir temperature for 42 days to displace oil until oil production stopped. The oil rate and percent of OOIP oil recovery was calculated using volume of oil expelled. The pH of brine and surfactant solution was ranged from 6.28 to 6.75. The possible effect of heat on the mass of the cores was neglected. The result is shown in chapter four.

3.8.2 Carbon Dioxide Flooding: Laboratory Study and Numerical Simulation

Fig. 9 shows the schematic diagram of the set-up of CO_2 flooding experiment.

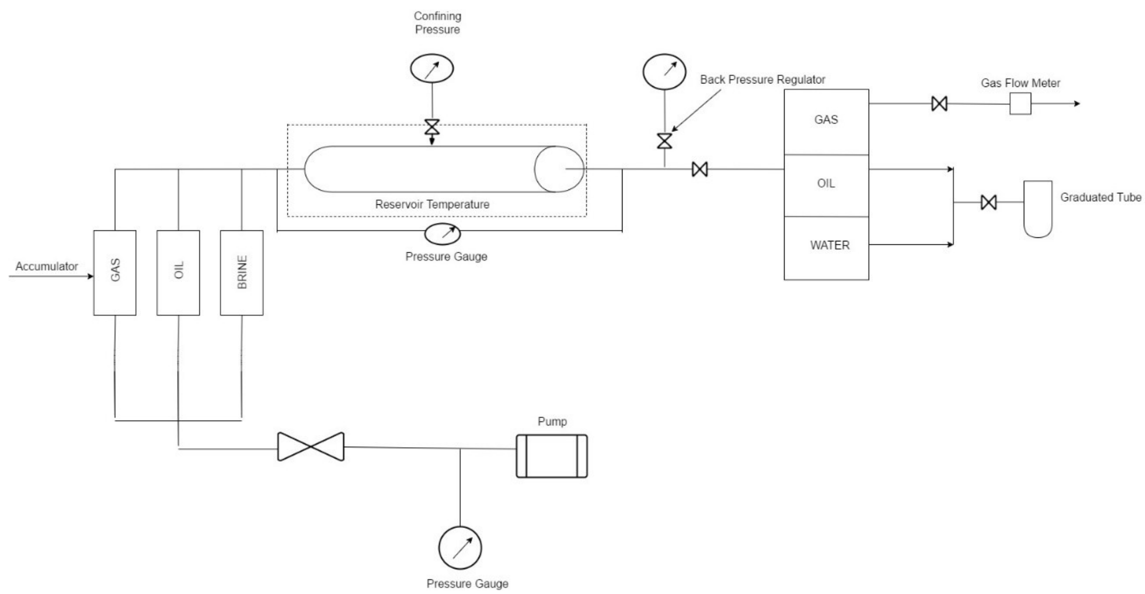


Fig. 9. CO_2 Core Flooding Experiment set up

* The saturated cores were prepared.

*The experiment was set as described in the schematic diagram.

* The carbon dioxide gas was put in the accumulator.

* The core was put in the hassler cell and assembled.

* The temperature was about 100 degrees Celsius.

* The confined pressure of 4000 psi (Bottom Hole Pressure at the formation)

* The gauge pressures at the inlet and the outlet of the core were being monitored until it was sure they are the same, i.e., no differential pressure.

* The CO_2 was injected through the inlet part of the core to pass through the core and come out at the outlet side under pressure.

* Between the hours of 12:53:10 and 12:56:10, the differential pressure changed from 10.48917 psi to 41.1169 psi.

* Between the hours of 12:56:55 and 14:54:27, the differential pressure changed from 88.2932 psi to 1338.6726 psi.

* Between the hours of 12:56:55 and 14:54:27, the differential pressure changed from 88.2932 psi to 1338.6726 psi.

* At injection pressure of 2800 psi, the CO_2 and oil started coming out of the core.

* After this, the core was removed from the hassler cell, and reweighed.

*The recovery factor was calculated. The result is shown in Chapter 4.

Simulation of CO_2 Flooding Using Computer Modelling Group Software (CMG)

The CO_2 'HnP' numerical simulation was also carried out using different injection, saturation and production conditions. Computer Modelling Group (CMG) software was used in the Computer Lab of Leonard Hall, UND. The properties of the formation were input into the 'STARS' of the software and cases of simulations were run under different conditions. The results were exported, which shows good recovery using CO_2 flooding. The results are shown in Chapter 4.

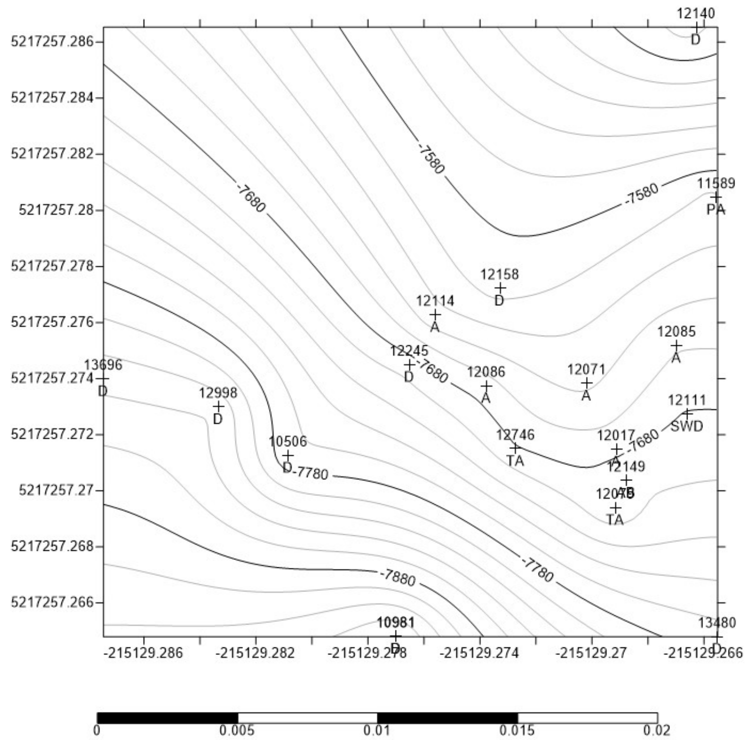
Table 5. The Conditions of the Reservoir for Well No. 12071

Properties	Values
Porosity of Matrix, POR MATRIX I, J, KVAR	0.07, 0.01, and 0.05
Permeability of Matrix, PERMK MATRIX I, J, KVAR	0.01, 15, and 116 (md)
Depth of Oil Water Contact, DWOC	9926 ft.
Average Water Saturation, SW	0.38
Well 1 'Injector'	'W-12071'
Well 2 'Producer'	'W-12071'
Temperature of Injected Water, TINJW	73 deg F
Pressure of Injected Water, PINJW	8000 psi
Matrix	Carbonate
Injecting Well:	Maximum Operating Borehole Pressure, OPERATE MAX BHP 8000 psi CONT REPEAT
Producing Well:	Minimum Operating Borehole Pressure, OPERATE MIN BHP 400 CONT REPEAT
Gas Phase Rate	OPERATE MAX STG-VARIES
Oil Phase Rate	OPERATE MAX STO - VARIES

4.0 RESULTS AND DISCUSSION

4.1 Geology of Dawson Bay Formation, Dolphin Field, Divide County, North Dakota.

4.1.1. Geologic Structures of Dolphin Field

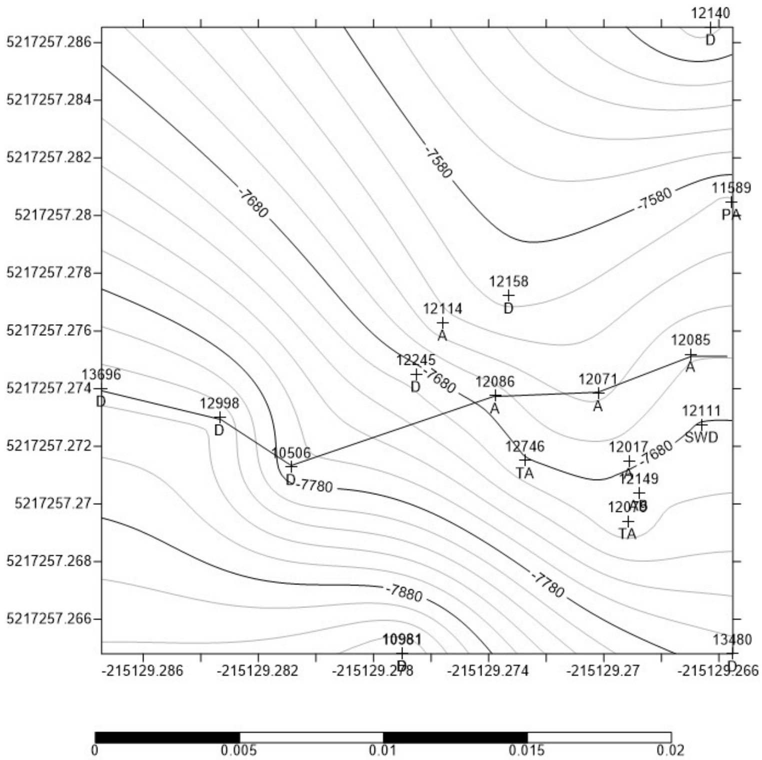


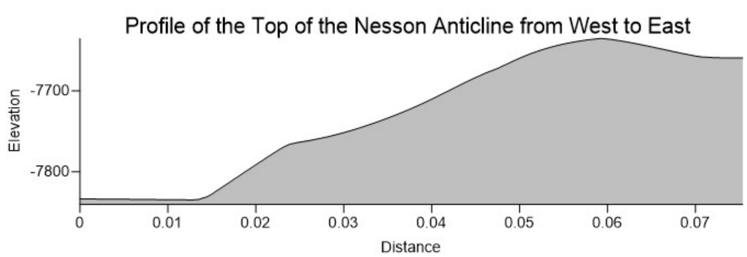
Legend

D	Dry Well
A	Active Well
TA	Temporarily Abandoned Well
PA	Plugged and Abandoned
SWD	Salt Water Disposal Well

Fig. 10. Contour of top of the reservoir rocks of Dawson Bay Formation in Dolphin Field and some neighboring wells

Fig. 10 shows the contour of the top of reservoir rock (porous rock below the anhydrite seal cover of the formation holding oil. It shows the trend of the Nesson Anticline on the Eastern part of the field. The contour does not show closure. This makes it difficult to ascertain the structural nature of the hydrocarbon trap.



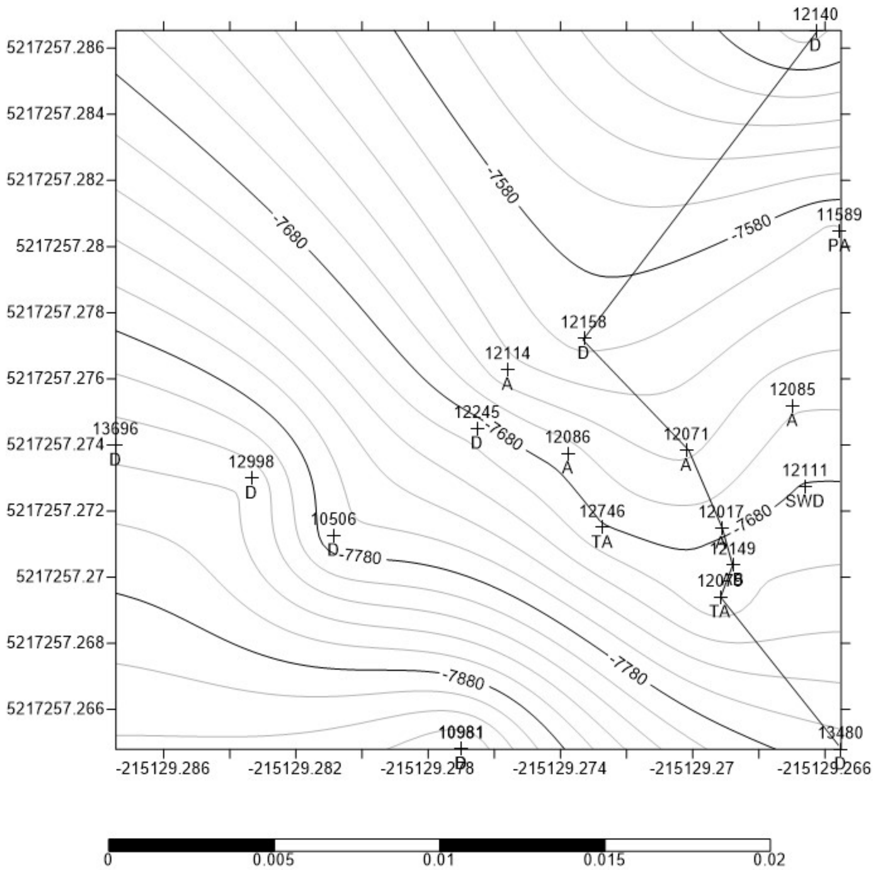


Legend

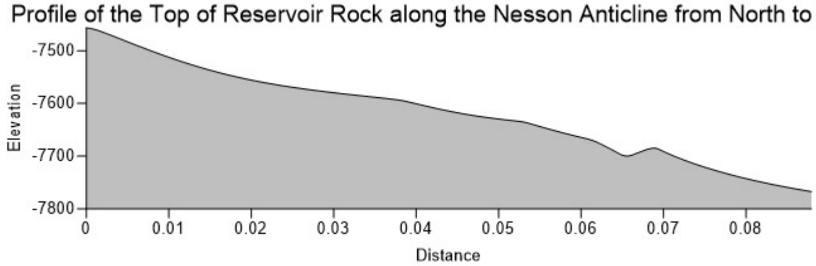
D	Dry Well
A	Active Well
TA	Temporarily Abandoned Well
PA	Plugged and Abandoned
SWD	Salt Water Disposal Well

Fig. 11. Profile of top of reservoir rock across Nesson Anticline from West to East.

Fig. 11 shows the profile of the top of reservoir rock across the Nesson Anticline from West to East, it mimics the traverse cross-section of an anticline



Profile of the Top of Reservoir Rock along the Nesson Anticline from North to South



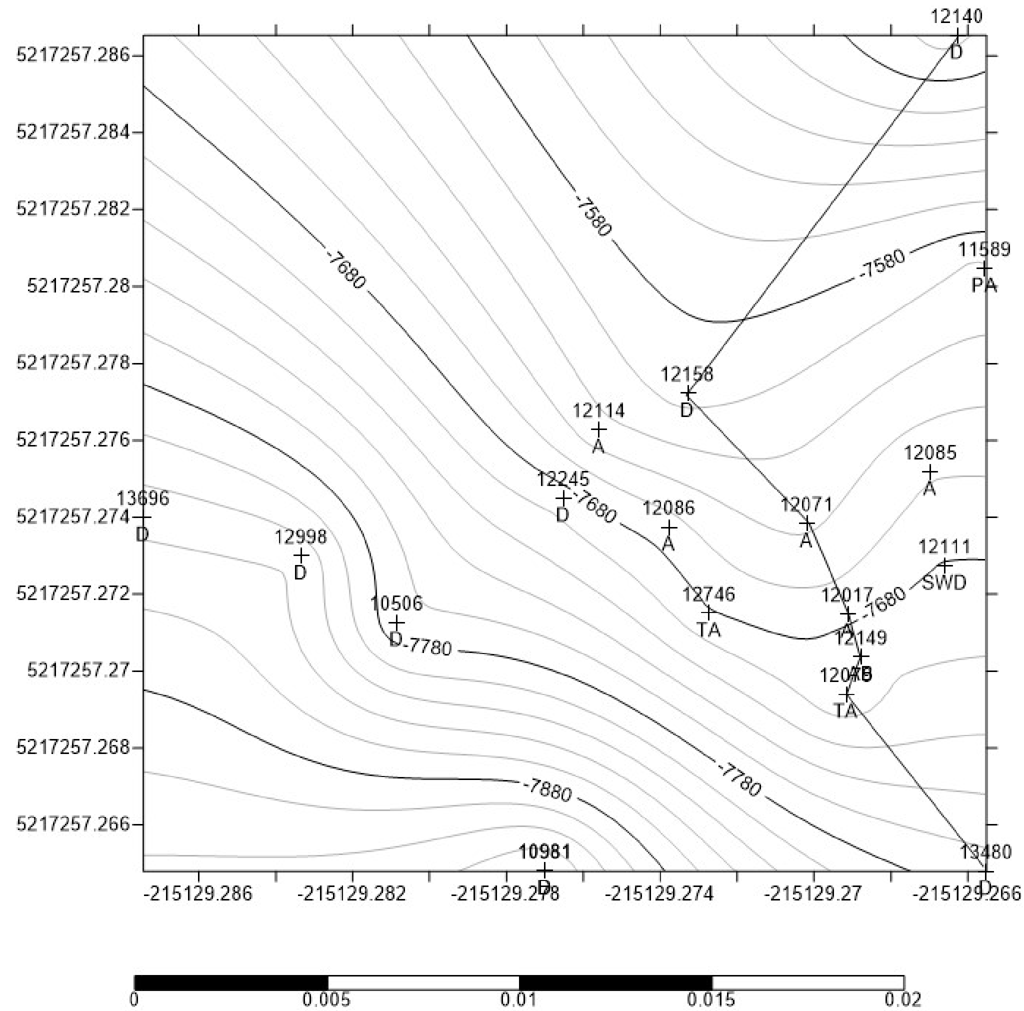
Legend

D	Dry Well
A	Active Well

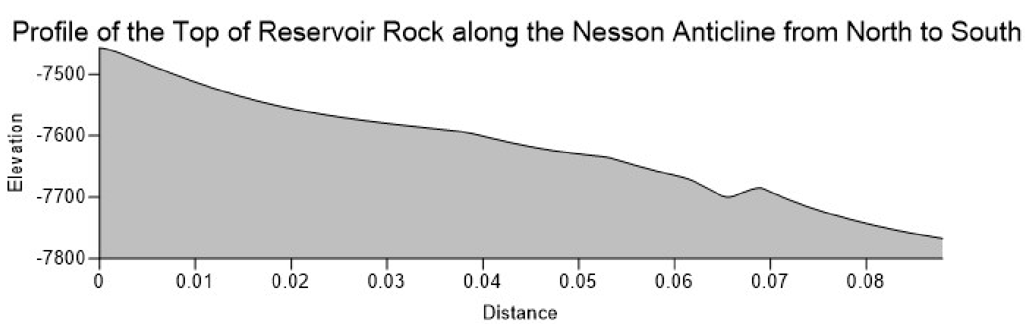
TA	Temporarily Abandoned Well
PA	Plugged and Abandoned
SWD	Salt Water Disposal Well

Fig. 12. Profile of top of reservoir rock along Nesson Anticline.

Fig. 12 shows the top of reservoir rock across Nesson Anticline. There is an image of dipping to the East mimicking the Nesson anticline. Fig. 13 shows the profile of the top of the reservoir in a Southeast direction along the anticline. It shows plunging southward.



-7580
-7680
-7780
-7880
12140 D
11589 PA
12158 D
12114 A
12085 A
12245 D
12086 A
12071 A
13696 D
12998 D
12111 SWD
10506 D
12746 TA
12017 A
12149
TA
10981 D
13480 D



Profile of the Top of Reservoir Rock along the Nesson Anticline from North to South
Elevation
Distance

Legend

D	Dry Well
A	Active Well
TA	Temporarily Abandoned Well
PA	Plugged and Abandoned
SWD	Salt Water Disposal Well

Fig. 13. Top of reservoir rocks along producing wells.

Fig. 13 shows the profile of the top of reservoir rocks along the producing wells. The profile mimics the shape of the anticline, it dips to the south like the anticline. The producing wells are on the peaks and sides of the structure.

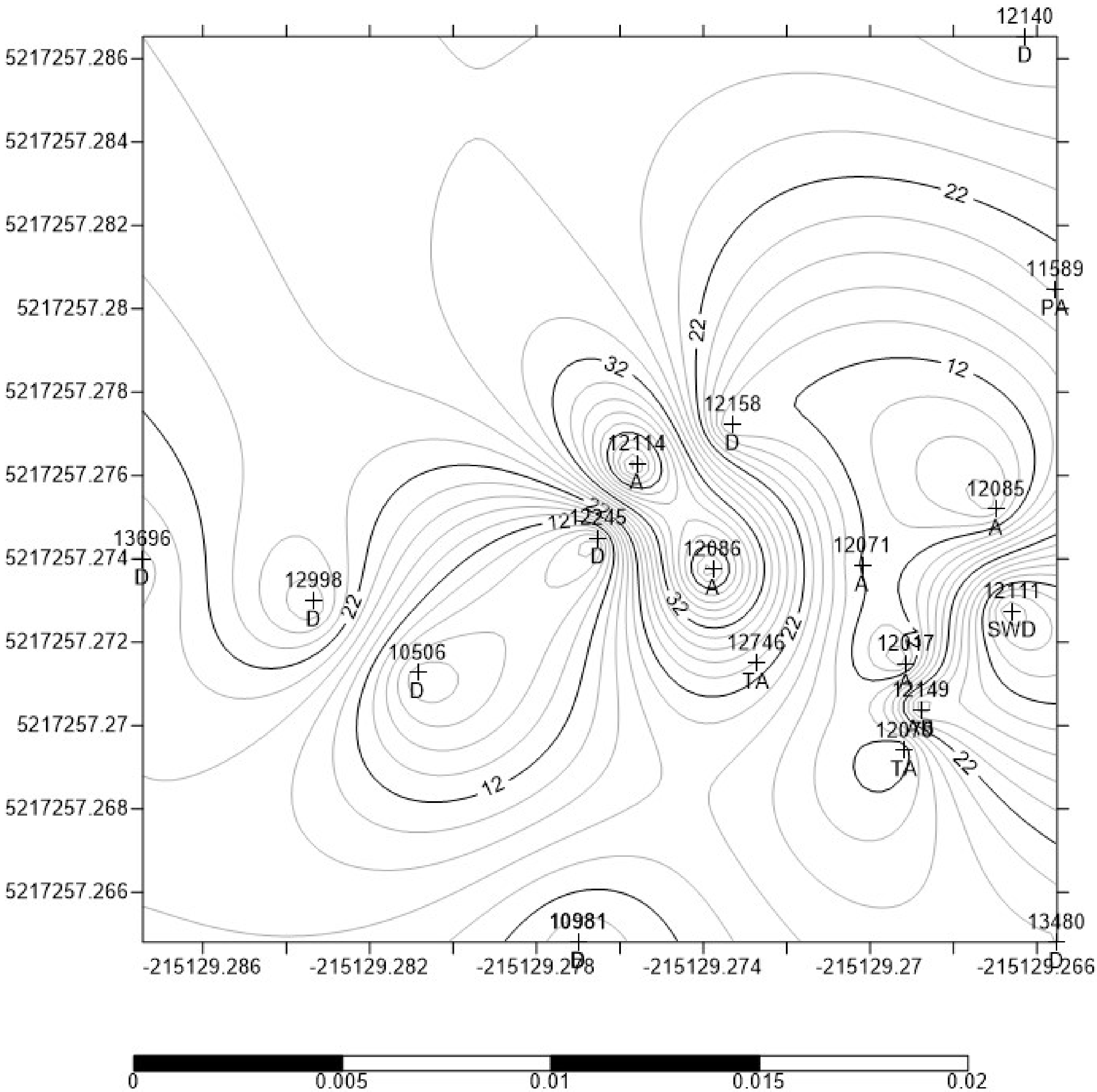
The producing wells are 12071, 12017, 12085, 12086, 12114, and 12149. Wells 12071, 12071 and 12149 are on top of the Nesson Anticline, and wells 12085, 12086 and 12114 are on the sides of the anticline. 12746 is Temporarily Abandoned and it is on the side of the Anticline. Well 12079, Temporarily Abandoned is on the southern part of the anticline. The neighboring wells outside Dolphin Field included in map creation are 10506, 12158, 12998, 13480 and 13696.

Production of Wells from Dawson Bay (DB) Formation

Wells 12071, 12086, 12114, 12149 are on the top of the anticline and productive of oil. Well 12158 on a peak is dry, and Well 12245, which is a little bit lower than Well 12086, but almost the same depth with 12746 is dry, while 12746 has produced oil though Interimly Abandoned (IA) now. Well 12017, a little higher than Well 12086 has produced from Dawson Bay (DB) Formation though it is IA now, and Well 12079, which has the same depth with Well 12746 has produced from DB Formation though IA now. In the Western side of the map, Well 13696 has never produced hydrocarbon from DB. Well 12998 which is located some distance away from the axis of the anticline has not produced hydrocarbon from DB Formation. Well 10506 is too far away from the axis, lower than Well 12998, and it has never produced from DB Formation. Well 13480 has not produced from DB Formation.

There is no seeming closure. The reservoir rock observed in the core description process has halite plugs. It can be inferred from these observations that the field is typical of a combination of somewhat structural and stratigraphic hydrocarbon traps.

Isopach Map of Reservoir Rocks in Dolphin Field and Some Neighboring Wells.



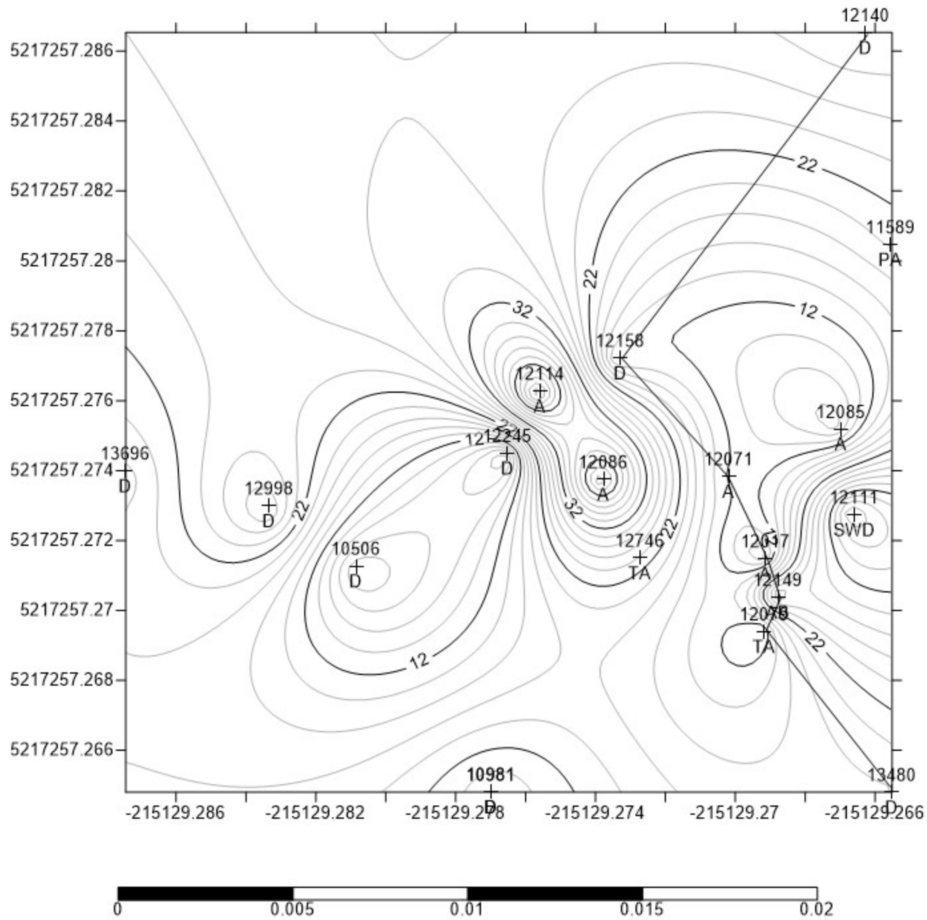
Legend

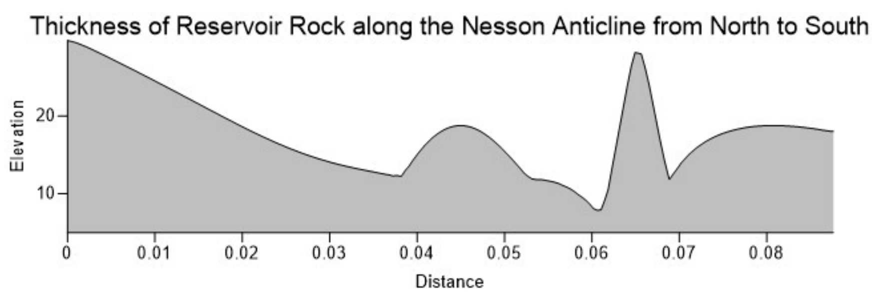
D	Dry Well
A	Active Well
TA	Temporarily Abandoned Well
PA	Plugged and Abandoned
SWD	Salt Water Disposal Well

Fig. 14. Isopach map of reservoir rocks in Dolphin Field and some neighboring wells.

There is variability in the thickness of the reservoir rock in Dawson Bay, Dolphin Field, as shown in Fig. 14.

The figure shows greatest thickness in the area with producing wells.



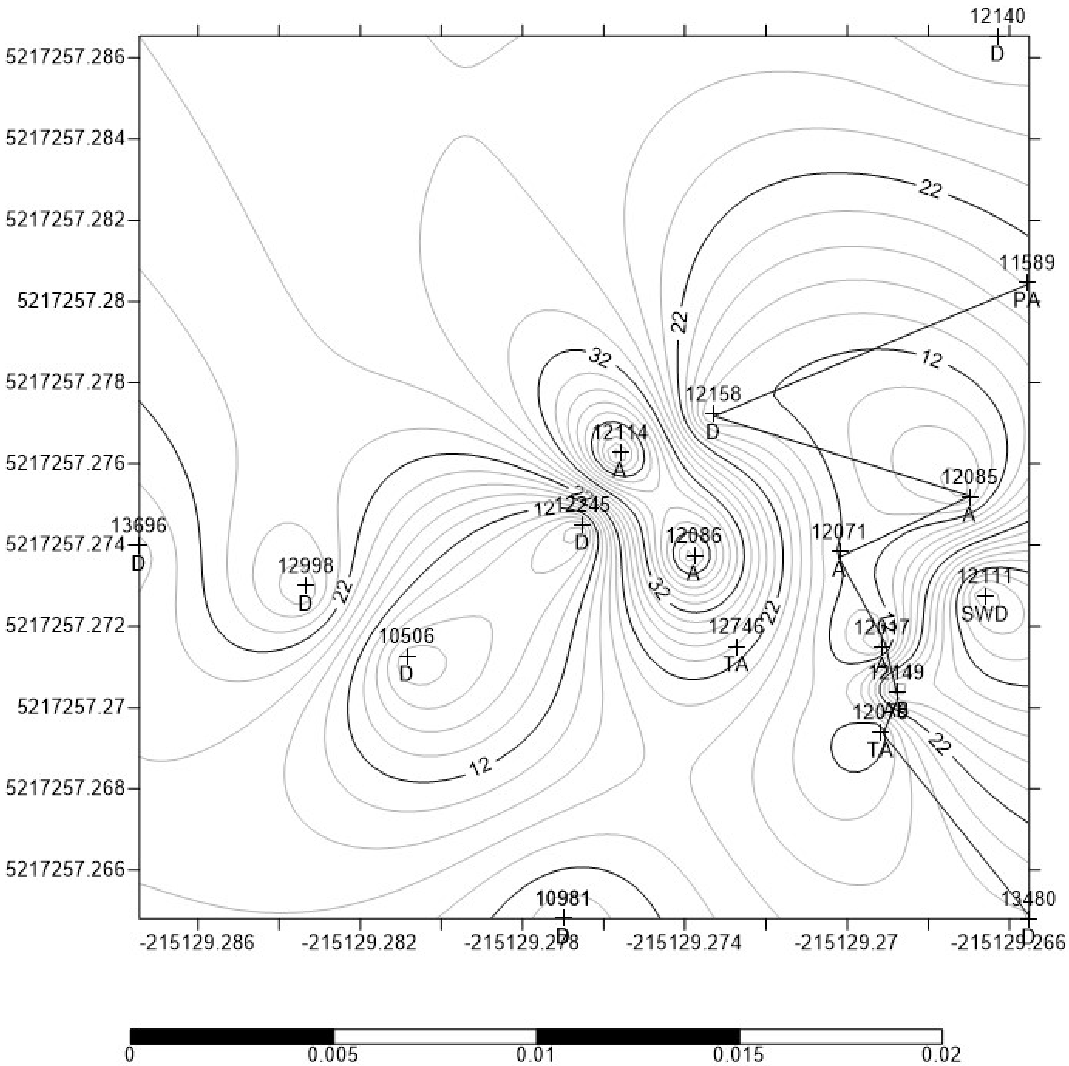


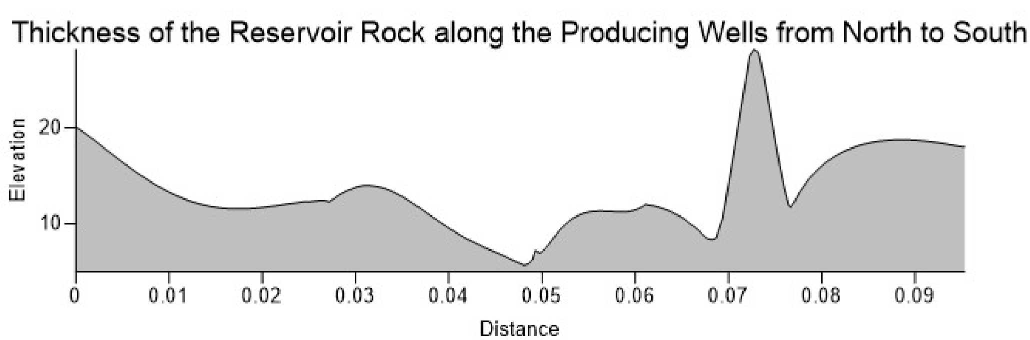
Legend

D	Dry Well
A	Active Well

TA	Temporarily Abandoned Well
PA	Plugged and Abandoned
SWD	Salt Water Disposal Well

Fig. 15. Isopach map of reservoir rocks in Dolphin Field and some neighboring wells along Nesson Anticline.


12140
D
5217257.286
5217257.284
5217257.282
5217257.28
5217257.278
5217257.276
5217257.274
5217257.272
5217257.27
5217257.268
5217257.266
22
11589
PA
32
12
12158
D
12114
A
12085
A
12245
D
13696
D
12086
A
12071
A
12998
D
32
12111
SWD
12746
TA
10506
D
12149
TA
12
10981
D
13480
D
-215129.286
-215129.282
-215129.278
-215129.274
-215129.27
-215129.266
0
0.005
0.01
0.015
0.02

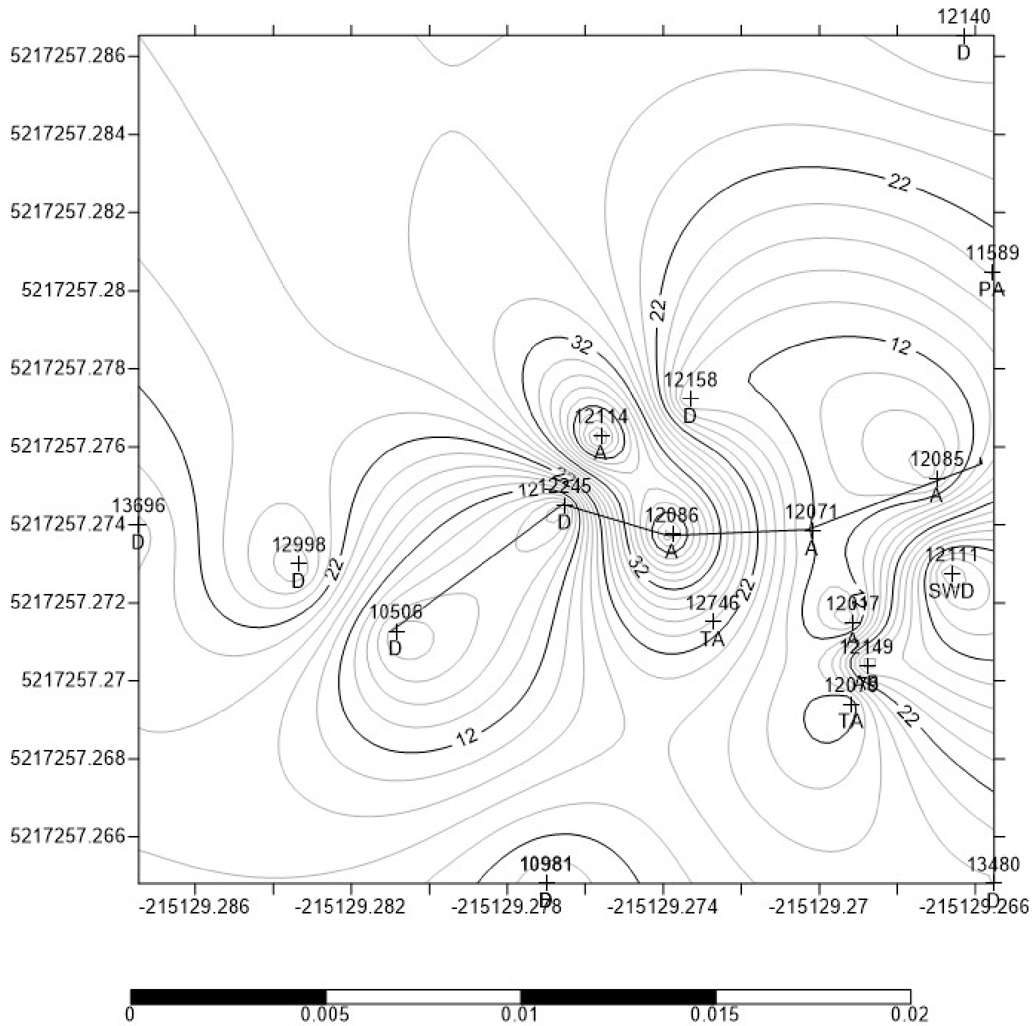

Thickness of the Reservoir Rock along the Producing Wells from North to South
Elevation
20
10
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
Distance

***

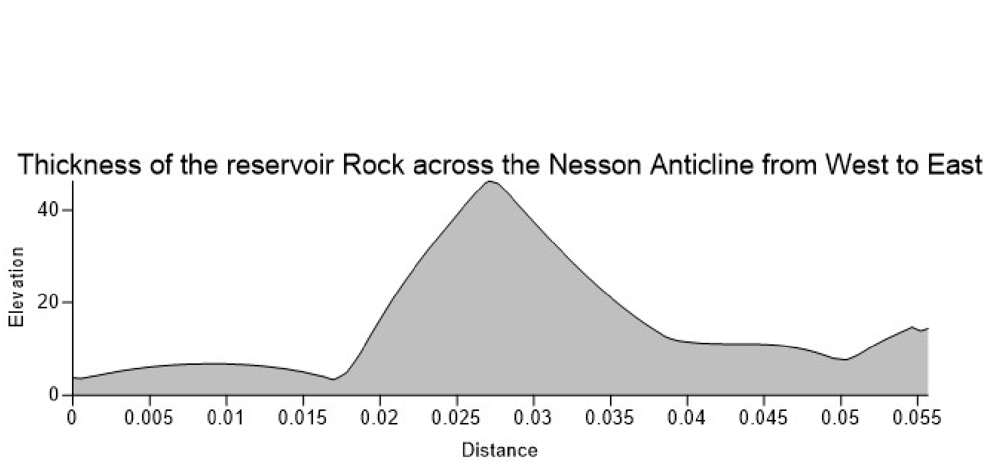
Legend

D	Dry Well
A	Active Well
TA	Temporarily Abandoned Well
PA	Plugged and Abandoned
SWD	Salt Water Disposal Well

The thickness of the reservoir rock along the direction of the Nesson anticline shows that there is variability in the thickness. The variability is shown with the peaks almost of the same height (i.e., thickness) this shows that there might have been an erosion action or different degrees of diagenesis on the relatively uniformly deposited reservoir rock.



12140
D
5217257.286
5217257.284
5217257.282
5217257.28
5217257.278
5217257.276
5217257.274
5217257.272
5217257.27
5217257.268
5217257.266
22
11589
PA
12
32
12158
D
12114
A
12085
A
13696
D
12086
A
12071
A
12998
D
12111
SWD
10506
D
12746
TA
12149
TA
12
10981
D
13480
D
-215129.286
-215129.282
-215129.278
-215129.274
-215129.27
-215129.266
0
0.005
0.01
0.015
0.02



Thickness of the reservoir Rock across the Nesson Anticline from West to East
40
20
0
Elevation
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
0.055
Distance

Legend

D	Dry Well
A	Active Well
TA	Temporarily Abandoned Well
PA	Plugged and Abandoned
SWD	Salt Water Disposal Well

Fig. 16. Isopach map of reservoir rocks in Dolphin Field and some neighboring wells across Nesson Anticline.

The thickness of the reservoir rock across the Nesson anticline varies from West to East, and it thins to the edges and thickens at the center. This probably contributed to the oil reservoir capacity of the reservoir rocks on the anticline.

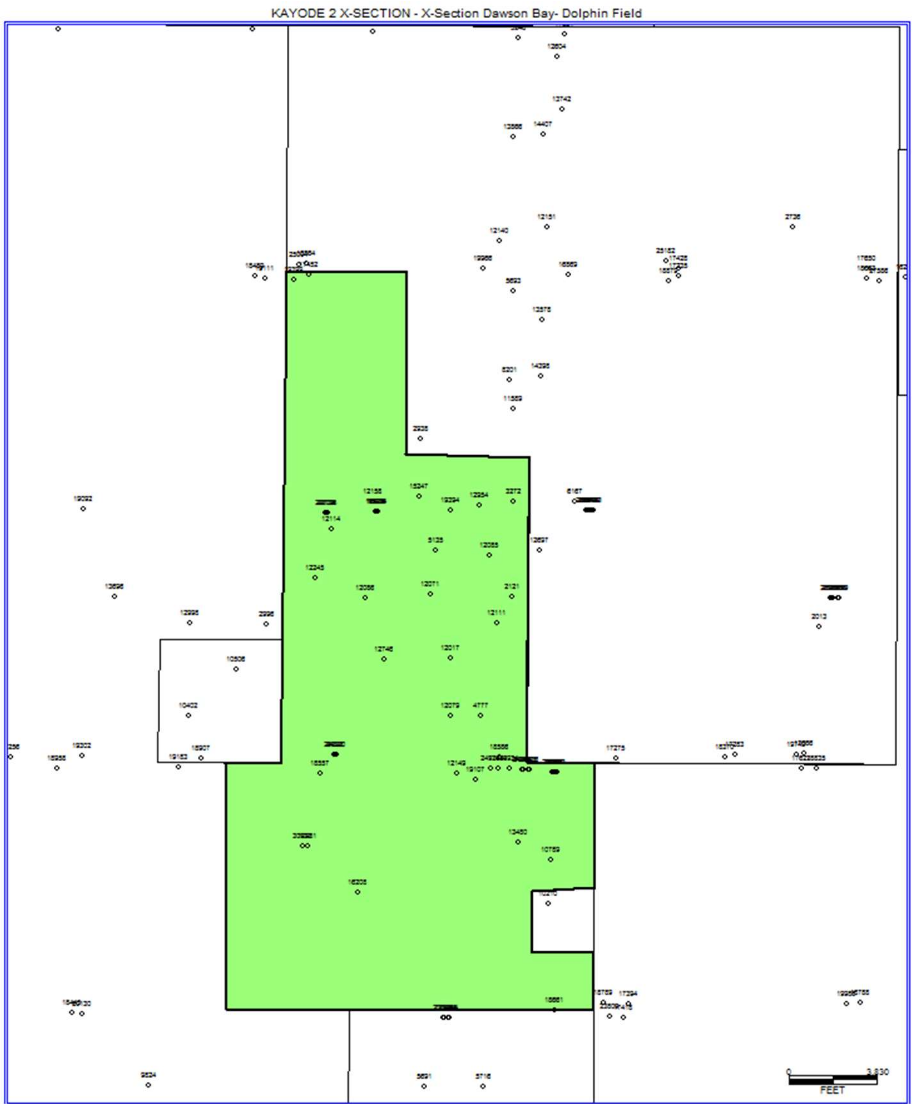


Fig. 17. Plan of Dolphin Field (NDIC, 2019).

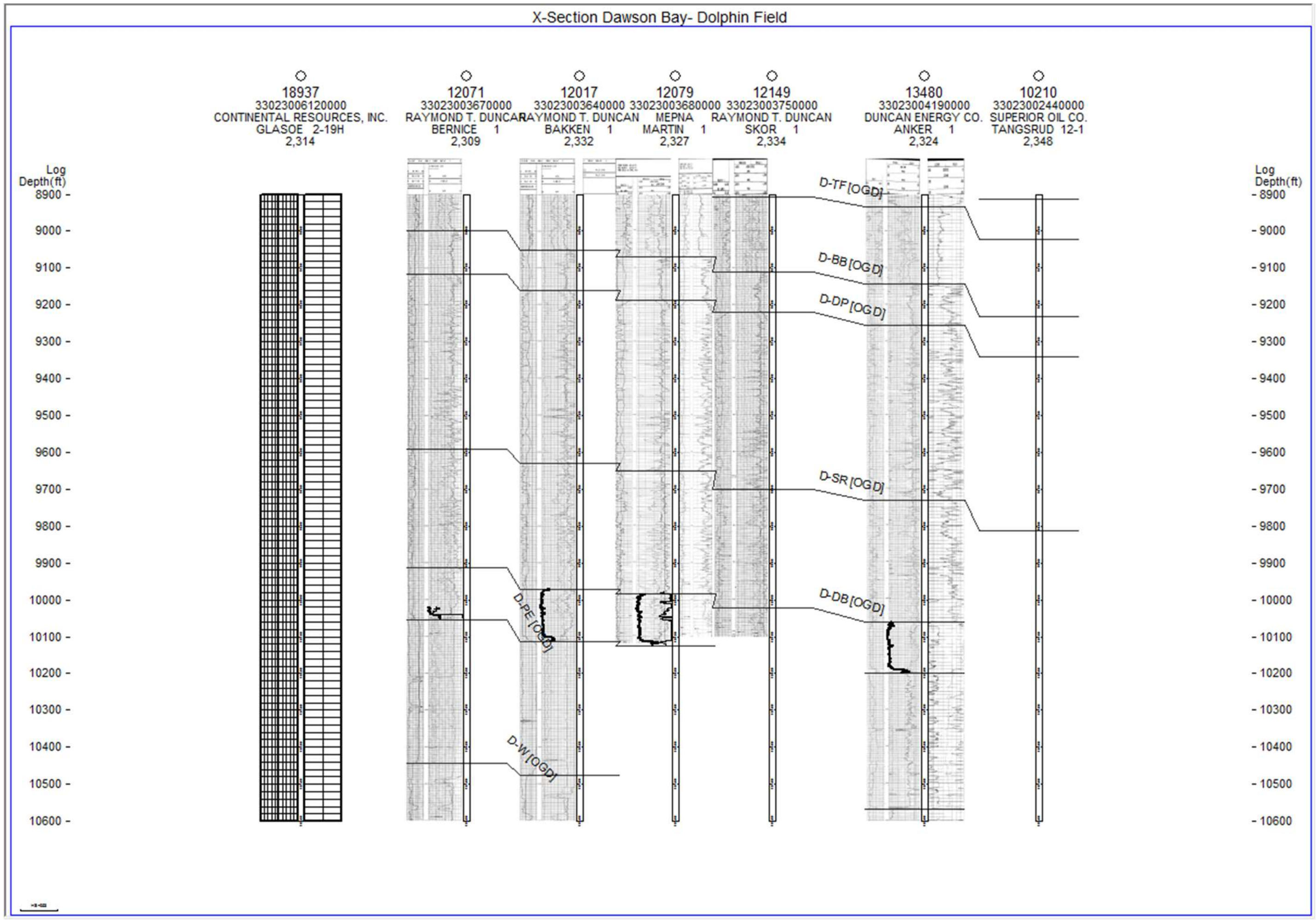


Fig. 18. Structural cross section of Dawson Bay Formation in Dolphin Field 1 (North -South).

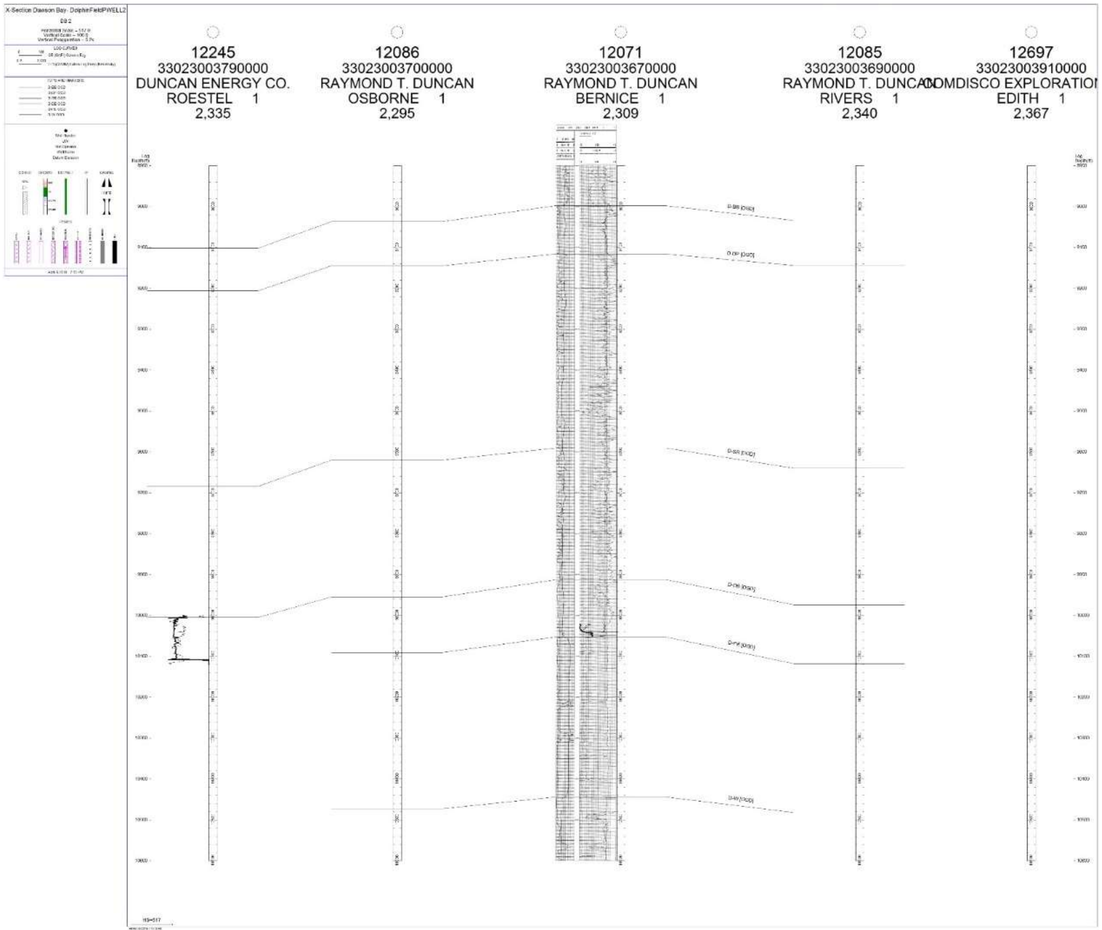


Fig. 19. Structural cross section of Dawson Bay Formation in Dolphin Field (East to West).

Fig. 18 shows the cross section of the Dawson Bay Formation along the wells 18937, 12071, 12017, 12079, 12149, and 13480 along the Nesson Anticline. It shows the anticline in the Eastern part of the field. The cross section shows that the anticline and the Dawson Bay Formation plunges southward. The thickness of the Dawson Bay Formation is relatively uniform along the anticline. Fig. 19 shows the cross section of the Dawson Bay Formation along wells 12245, 12086, 12071, 12085 and 12697, in the West to East direction. This shows a fold with an uplift at the center as mentioned by Laird and Folsom (1956).

4.1.2. Depositional History

Fig. 16 which shows the isopach map of reservoir rocks in Dolphin Field and some neighboring wells across Nesson Anticline shows that the thickness of the reservoir rock, predominantly dolomite, slightly limestone, thickens from about 12 ft to about 44 ft. The reservoir is thick at mid-eastern part of the field and thins on the sides. This may likely suggest the topography of the marine environment where the limestone was deposited before it was characterized for hydrocarbon accumulation by diagenesis. The thickness of the reservoir rock other than anhydrite is about 35 ft in Well 12071, 60 ft in Well 12085, 40 ft in Well 12086, 35 ft in Well 12114, and 50 ft in Well 12149.

Table 6. Core Description

Length (ft.)	Description
12071	
9911-9917.9	Anhydrite, fine grained, contains some dolomite which reacts with dilute HCl after scratching.
9917.9- 9938	Dolomite, organic rich, dark colored, fossilized, halite crystals, not prominently laminated, vuggy porosity, fine grained, react with HCl after scratching, Pyritization, golden brown specks.
12085	
9996-10019	Gray colored, dolomite, some wavy laminated, some bioturbation, some almost vertical cracks, halite crystals, some as big as 1 inch, fine grained
12086	
9969-9988	Dolomite, vuggy porosity, shining white grains, white crystals (halite) (8mm diameter)
9988-10021	Vuggy porosity, salt crystals, bioturbation
10021-10029	Dolomite (smooth at cut surface)
12114	
9929-9940	Dolomite laminated, light gray (almost white) colored
9940-9960	Dolomite, almost white colored (very light gray), vuggy porosity, small quartz crystals
9960-9989	Dolomite, darker (dark gray colored), bioturbation, small quartz crystals (about 1 mm)
12149	
10042-10086	Dolomite, fine crystalline with calcite crystals (some as big as 1 cm diameter), vuggy porosity

4.1.3 Lithofacies and Diagenetic Description

The logs and core description results show that the Dawson Bay Formation looks regressive with the evaporite capping the crystalline carbonate, dolomite. The subaqueous anhydrite indicates evaporite low system tract which was formed during low sea level that led to the deposition of gypsum which was recrystalized to anhydrite (Hussinec, 2016). The thickness of each layer which is more than a few meters is an indicator that the depositions are not under tidal influence but marine. Tidal-flat deposition commonly results in cyclical packages of individual units only 1 m or more in thickness, whereas in the sub-marine environment, facies are likely to be thicker and grain-size variations are less abrupt (Shinn, 1983).

The vugs are characteristic of diagenesis, pyritization (golden) is present in parts of the dolomitized rock. This shows the remains of once living organisms, Raiswell (1997) says that formation of pyrite is common with fossils where the organic material decays by sulphate reduction, or where the carbonate skeleton either acts as a nucleation substrate or induces iron sulphide precipitation by dissolution. The diagenesis is so extensive that it has obliterated most of the structure of deposition of the formation. Figs. 24 to 29 show the plane and polarized view of the thin sections of the depths of wells in the Dawson Bay Formation.

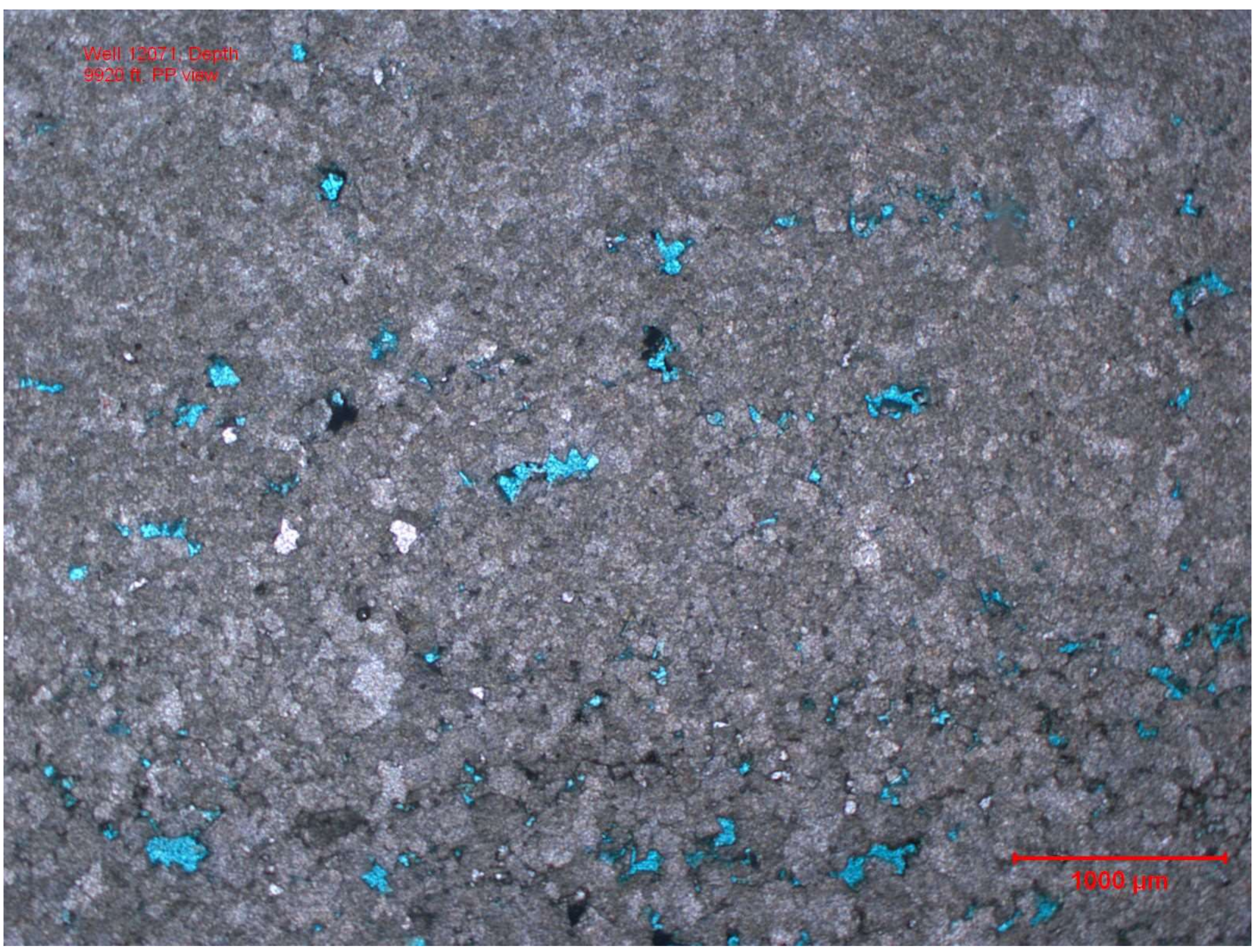


Fig. 20. Well 12071: 9920 ft. Plane Polarized View

The figure shows the pore spaces in blue colors. The large ones, vugs, are bold and some are as large as about 500 microns in length and about 80 microns in width.

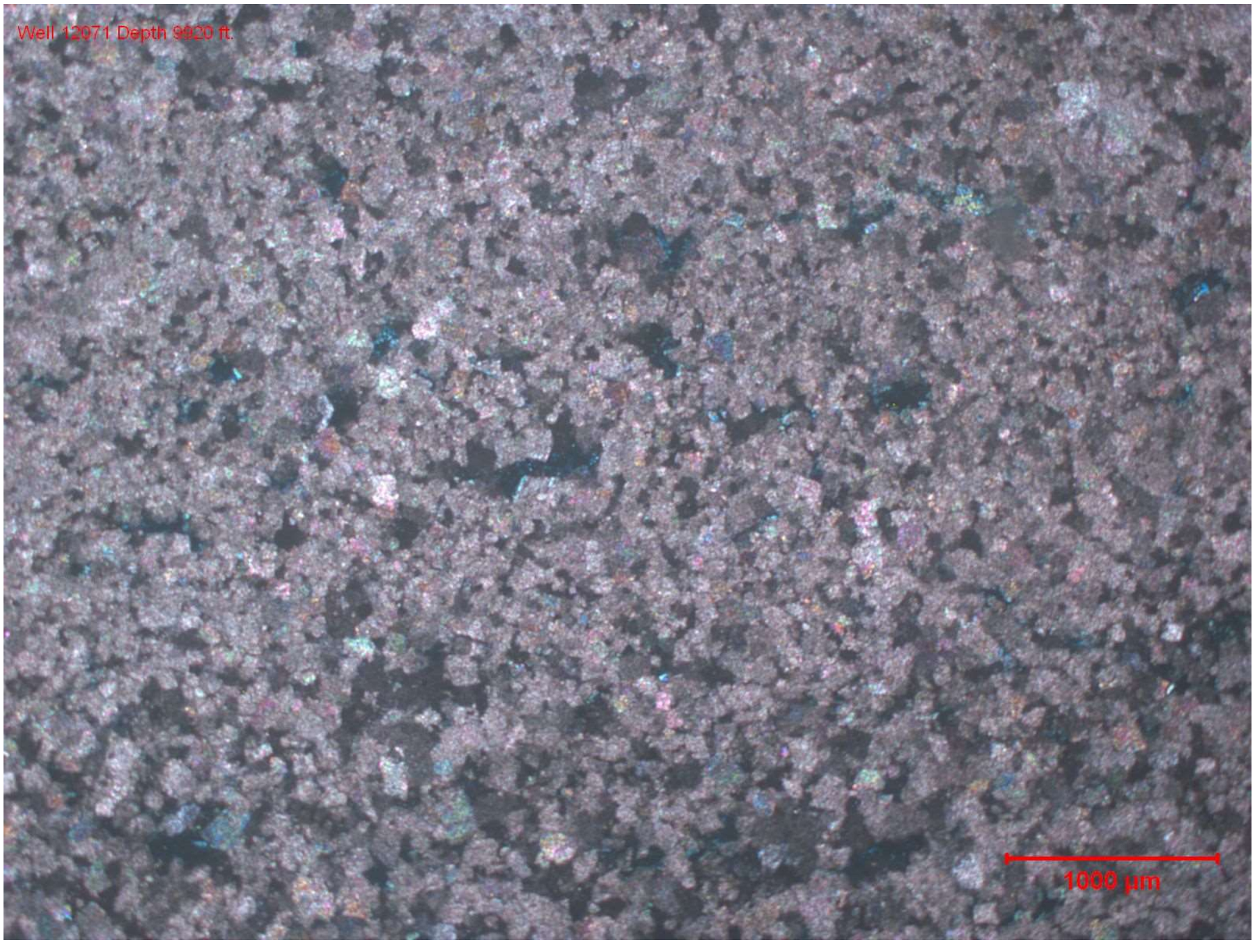


Fig. 21. Well 12071: 9920 ft. Cross Polarized View

The figures show the pore spaces. In plane polarized view, the pore spaces are shown in blue. The large ones, vugs, are bold and some are as large as about 500 microns in length, and about 80 microns in width. The two figures show the crystalline size crystals of dolomite.

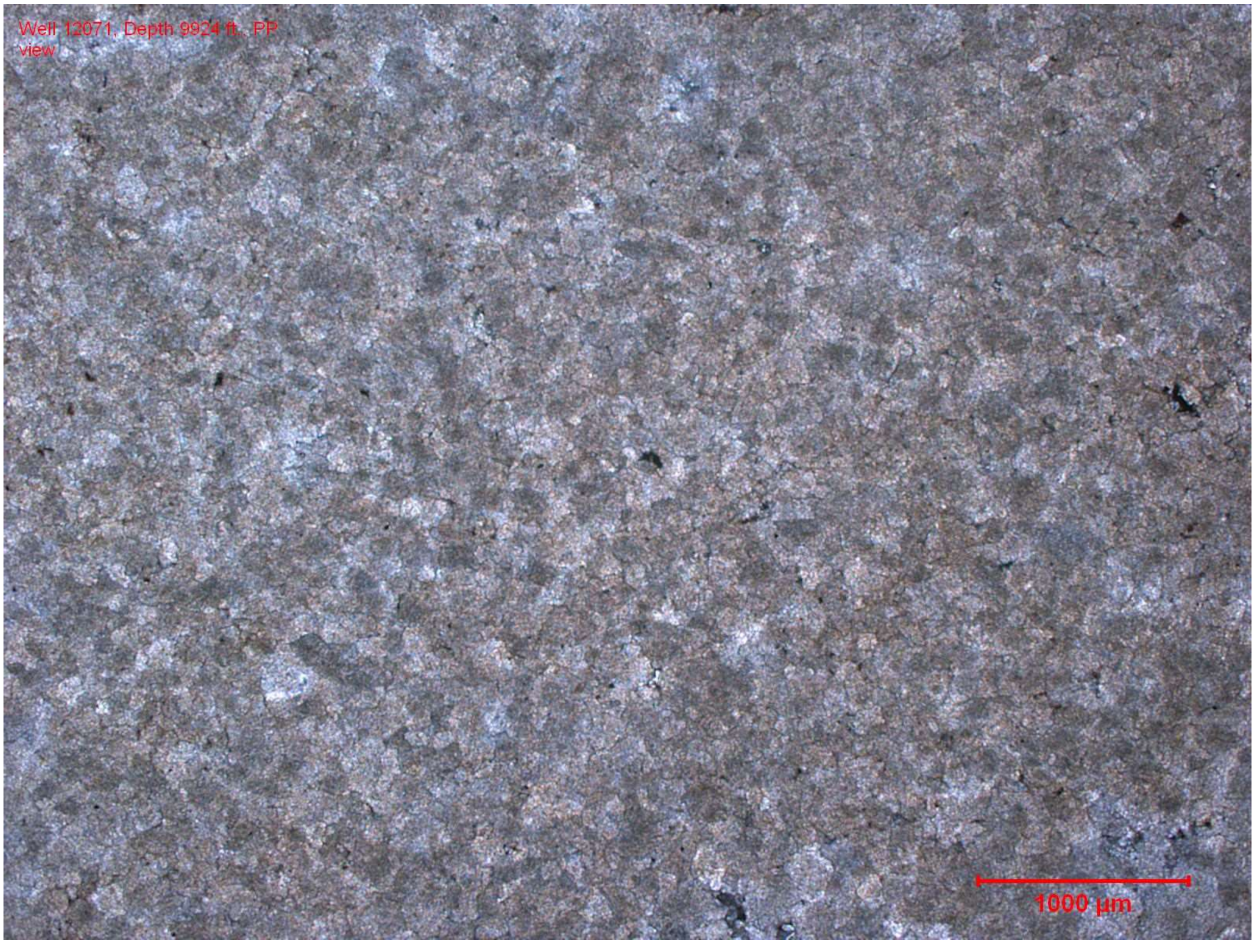


Fig. 22.   Well 12071: 9924 ft. Plane Polarized View

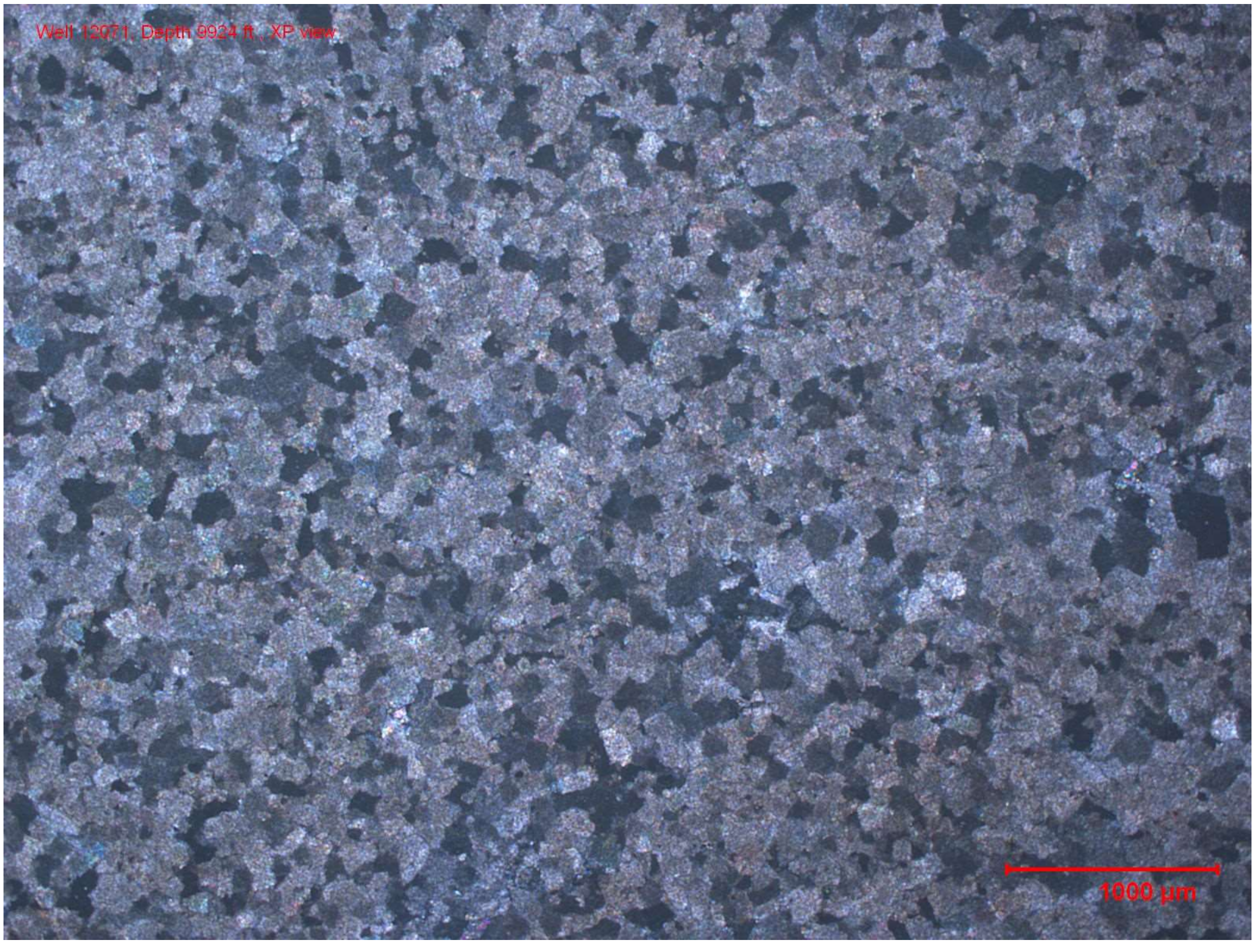


Fig. 23. Well 12071: 9924 ft. Cross Polarized View

The figures show the pore spaces in blue colors in plane polarized view. The two figures show the crystalline size crystals of dolomite.

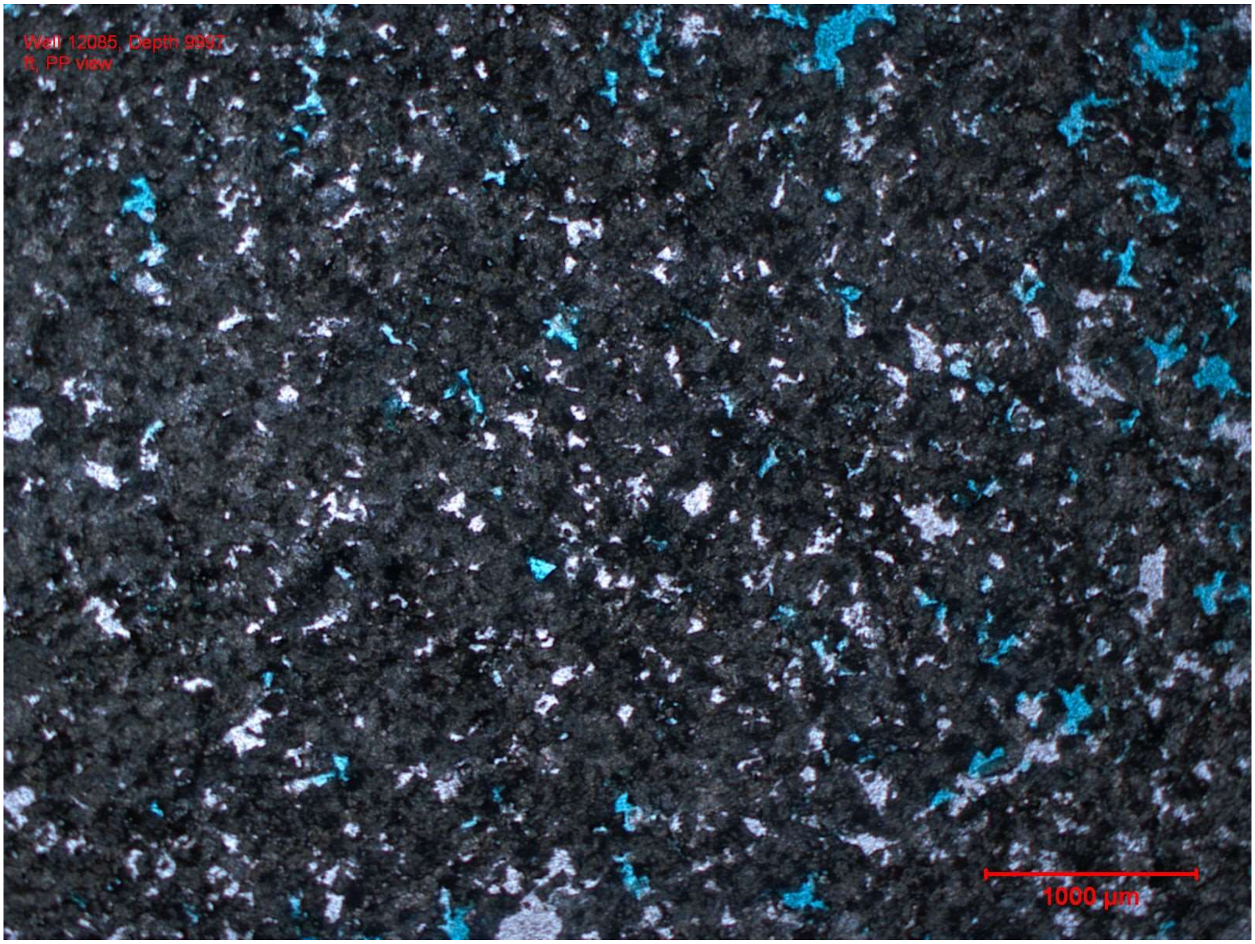


Fig. 24. Well 12085: 9997 ft. Plane Polarized View

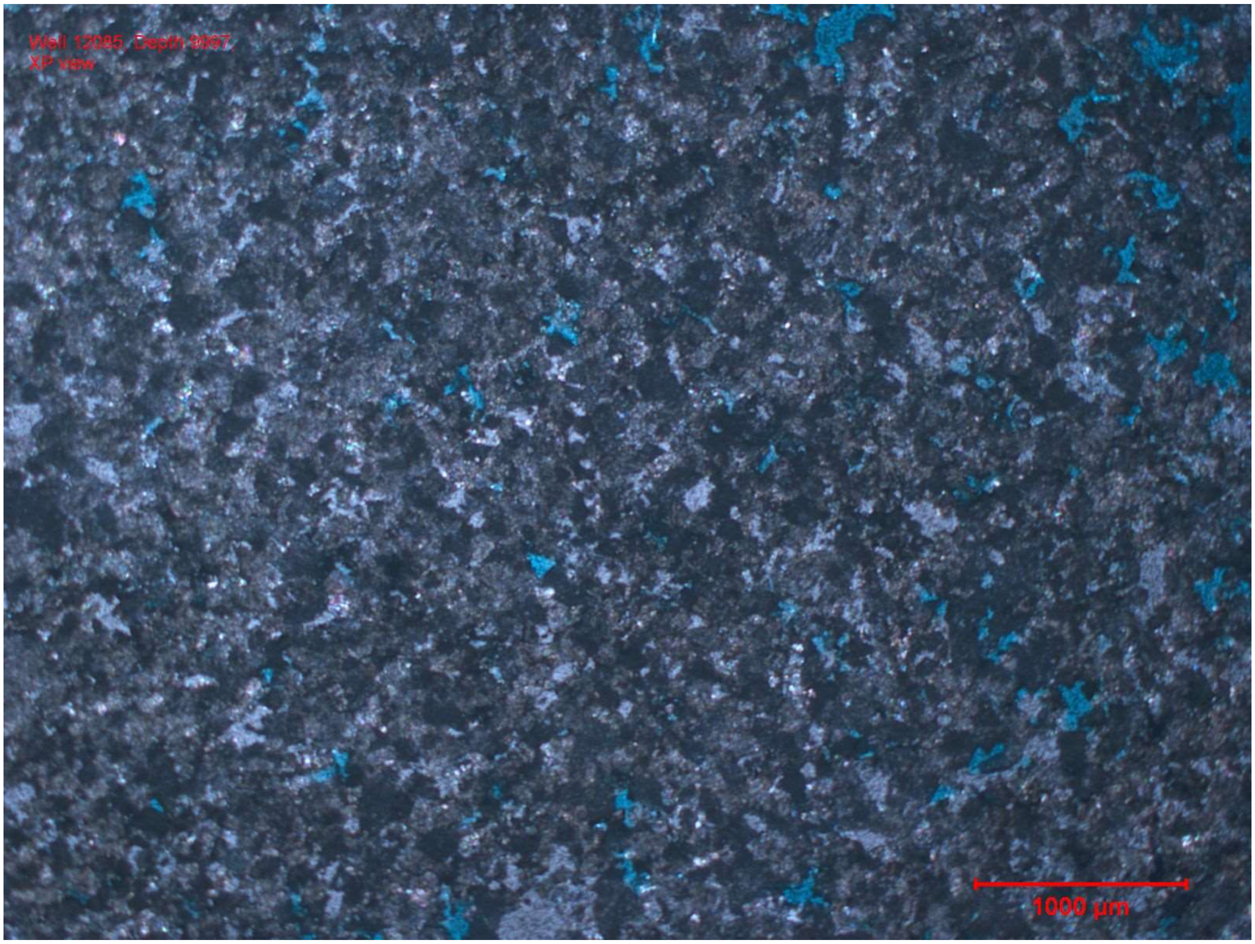


Fig. 25. Well 12085: 9997 ft. Cross Polarized View

The figures show the pore spaces. In plane polarized view the pore spaces are shown in blue. The large ones, vugs, are bold and some are as large as about 500 microns in length, and about 80 microns in width. The two figures show the crystalline size dolomite.

Summary of the Cores Examination and Description

The cores from Dawson Bay Formation for wells 12071, 12085, 12086, 12114, 12149 and 12158 are available in the Wilson Laird Core Library and they were checked. The observation was described in Table 5. The cores show predominantly dolomite rocks characterized heavily with vuggy porosity. They are gray to dark in color showing organic richness. Some are halite plugged limiting the permeability and are mostly capped with anhydrite.

It appears that the Dawson Bay Formation is of shallowing upward succession of limestone marine depositional environment, on a low relief platform, the limestone facie later diagenesed extensively to dolomite. The capped anhydrite is suggested to come from shallow continental shelf environment facie, and they eventually relate vertically as described by Walther’s Law.

4.1.4 Core Photos and Corresponding Depths on Logs

Well 12071

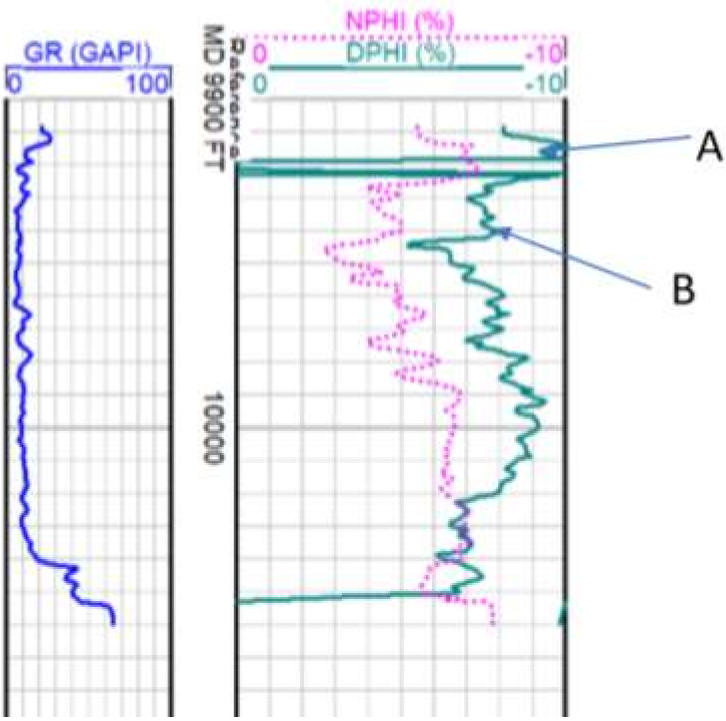


Fig. 26. CND log of Well 12071

Fig. 27. Core A: Laminated Anhydride

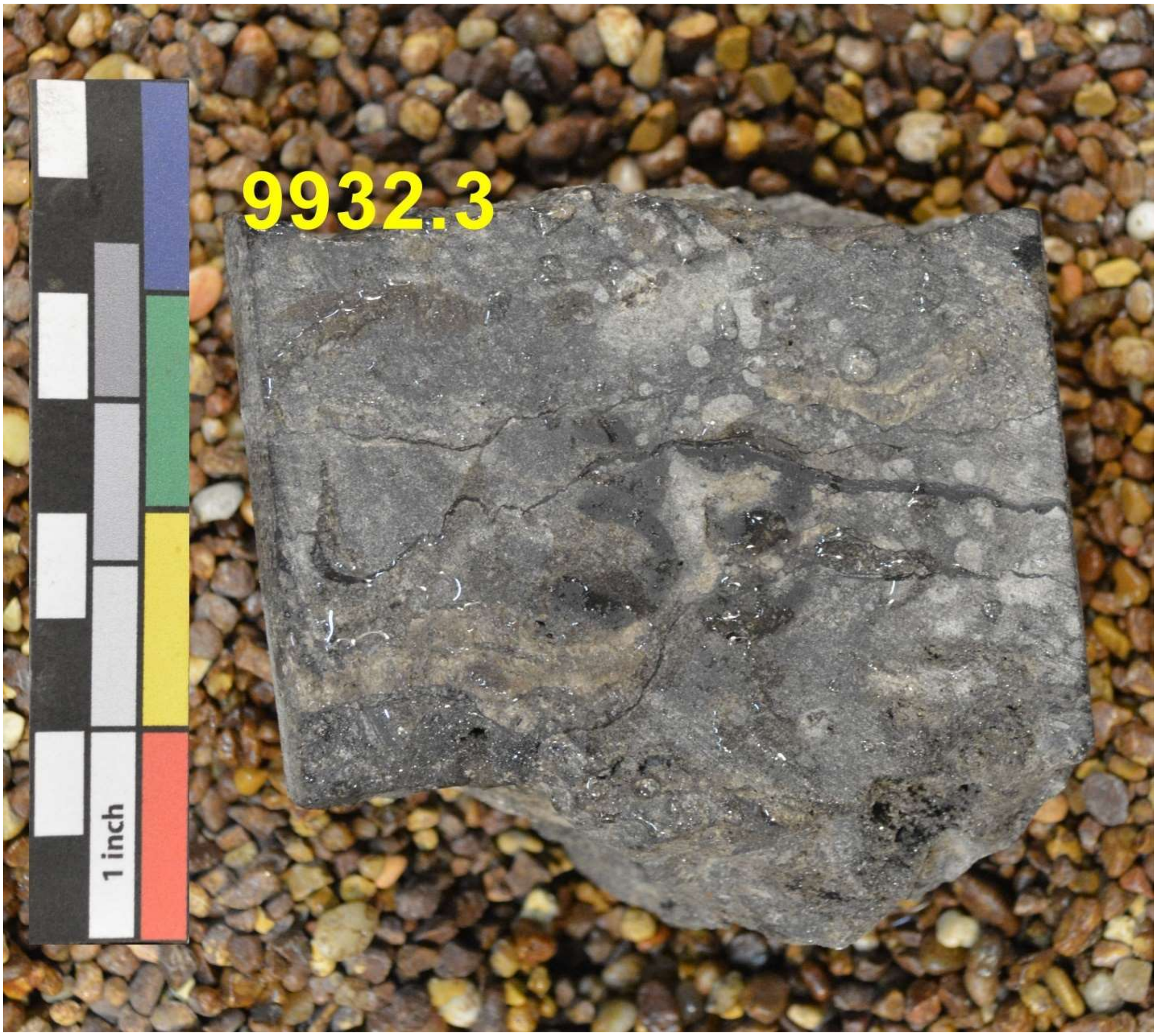


Fig. 28. Core B: Dolomite

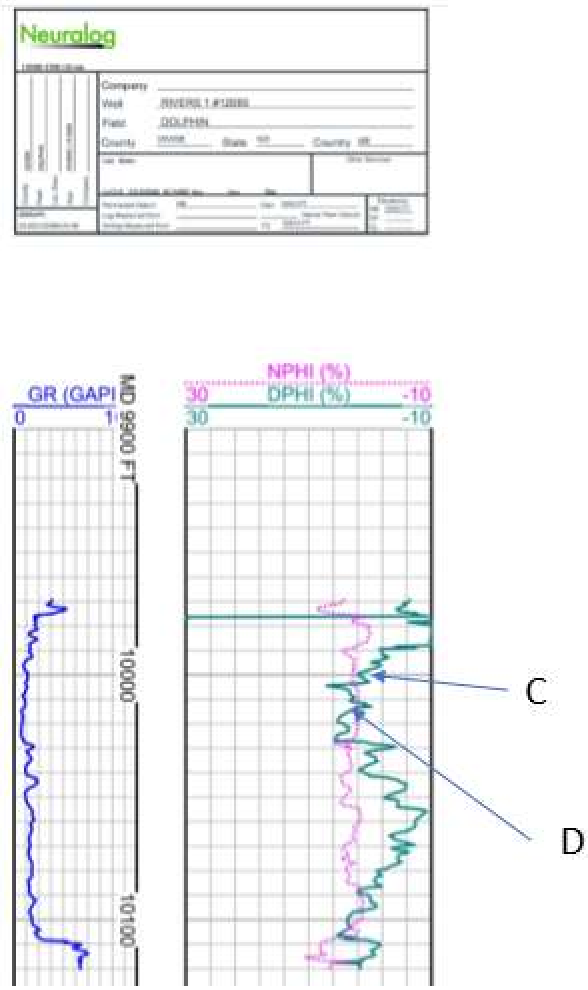


Fig. 29. CND log of Well 12085

Fig. 30. Core C: Dolomite

Fig. 31. Core D: Dolomite

4.2 Petrophysical Properties

The data was obtained from the logs from the calculation using Petra software by inputting the data of CND and LLD digitized logs. The logs data and core properties were obtained from the well files of the North Dakota Industrial Commission. Table 6 shows the results of these petrophysical properties, which show deviation of values from log analysis to be different from values from core analysis. The correlation value was also too low to show a reliable relationship.

Table 7 shows Cross Section of Porosity from Core Analysis and Conventional Logs.

Table 7. Porosity Values from Cores and Logs

S/No	Depth (ft.)	Core Porosity (%)	Porosity from Conventional Logs (%)
Well No 12071			
1.	9919.0	6.9	7.109
2.	9924.5	4.6	4.602
3.	9930.0	0.6	6.806
4.	9931.0	0.5	6.83
Well No 12114			
1.	9956.5	8.7	6.309
2.	9964.8	8.5	5.033
3.	9965.2	6.5	5.207
4.	9980.5	4.1	8.916

The values of the porosity of the formation at depths show deviation of values from log analysis and core analysis values. The correlation value was also too low to demonstrate a reliable relationship. The correlational coefficient for depth 9917 to 9932 ft with 0.5 ft incremental for well 12071 is about -0.1932, while for well no 12114, it is -0.77351. These results do not show a good relationship.

The above described result is different from the report of Adaeze et al. (2012) who did similar work on a sandstone deposit in the Niger Delta Basin, Nigeria. They obtained good values and good correlation which can be used to establish a relationship for offset wells.

Marchant and White (1968) report that when log and core analysis of carbonate of Ratcliffe Interval from the Madison Formation in Montana's Flat Lake Oil Field were compared, accurate evaluation was difficult due to heterogeneity of the formation and presence of vugs. The results were greatly deviated. Sharma et al. (2012) tried to proffer solutions to problems faced in Well Log Analysis in Carbonate Reservoir Systems because of multiple porosities and lithologies, they recommended integrating core analysis with log results and use of Nuclear Magnetic Resonance logging, which calculates porosity not based on lithology. Salazar and Romero (2001) reported that porosity from NMR logs correlated with data from conventional core analysis on carbonate cores, and they used ANN to predict the porosity for the neighboring well.

Table 8 shows the result of cross plot for cross section of wells 12071 and 12114.

Table 8. Cross Section of Porosity and Lithology from Core and Neutron-Bulk Density Cross Plot.

S/No	Depth (ft.)	Core Porosity (%)	Porosity from Neutron-Bulk Density Cross Plot (%)	Lithology from Neutron-Bulk Density Cross Plot	Lithology from Core Analysis
Well No 12071					
1.	9919.0	6.9	1.542	Anhydride-Dolomite	Anhydride-Dolomite
2.	9924.5	4.6	5.313	Dolomite-Limestone	Dolomite
3.	9930.0	0.6	11.548	Dolomite-Limestone	Dolomite
4.	9931.0	0.5	13.04	Dolomite-Limestone	Dolomite
Well No 12114					
1.	9956.5	8.7	7.267	Limestone	Dolomite
2.	9964.8	8.5	7.219	Dolomite-Limestone	Dolomite
3.	9965.2	6.5	6.625	Dolomite-Limestone	Dolomite
4.	9980.5	4.1	8.686	Dolomite-Limestone	Dolomite

The results show discrepancies.

Bertrand et al. (1967) recommended the use of the multiple regression method on logs and core data to predict reservoir properties like porosities from carbonate formation with vugs.

Lashin and El Din (2013) used ANN to predict porosity using conventional logs. The result of using ANN on conventional logs: Compensated Neutron Density, Density Porosity and Bulk Density in this study is shown on Fig. 32.

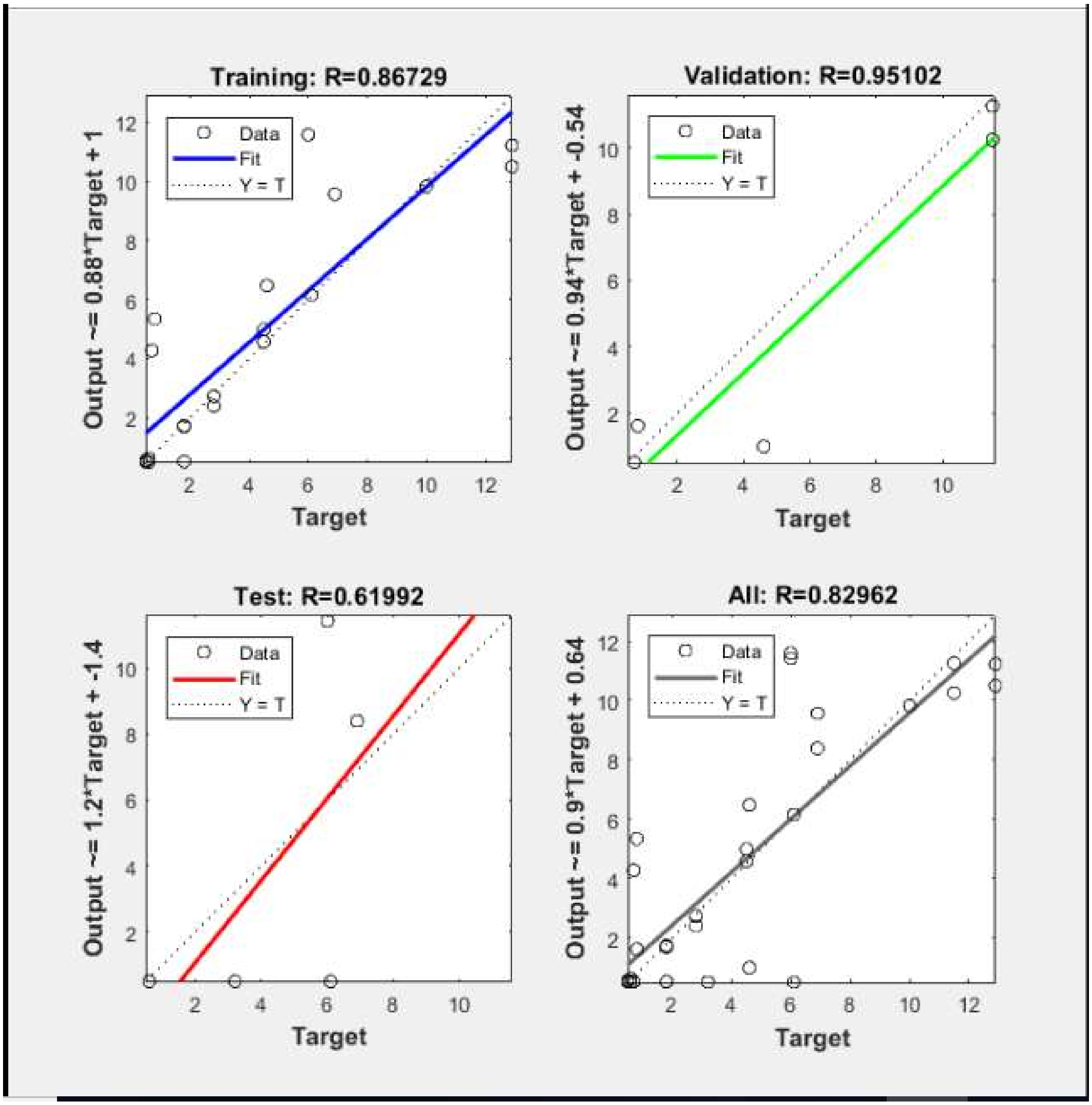


Fig. 32. Result of ANN on Well 12071.

log porosity = 0.9 * core porosity + 0.64 (R=0.82962). This can be used to predict the porosity for other parts of the well where there are no values from core analysis.

Olayiwola (2017), Kohli and Arora (2014) recommend the use of Artificial Neural Network for estimation of petrophysical properties of heterogenous oil reservoir formations in order to obtain reliable values.

Result of Nuclear Magnetic Resonance T2 Relaxation Tests for porosity on cores used for the experiment.

Fig. 33 shows the T2 relaxation time graphs for core sample 71-2.

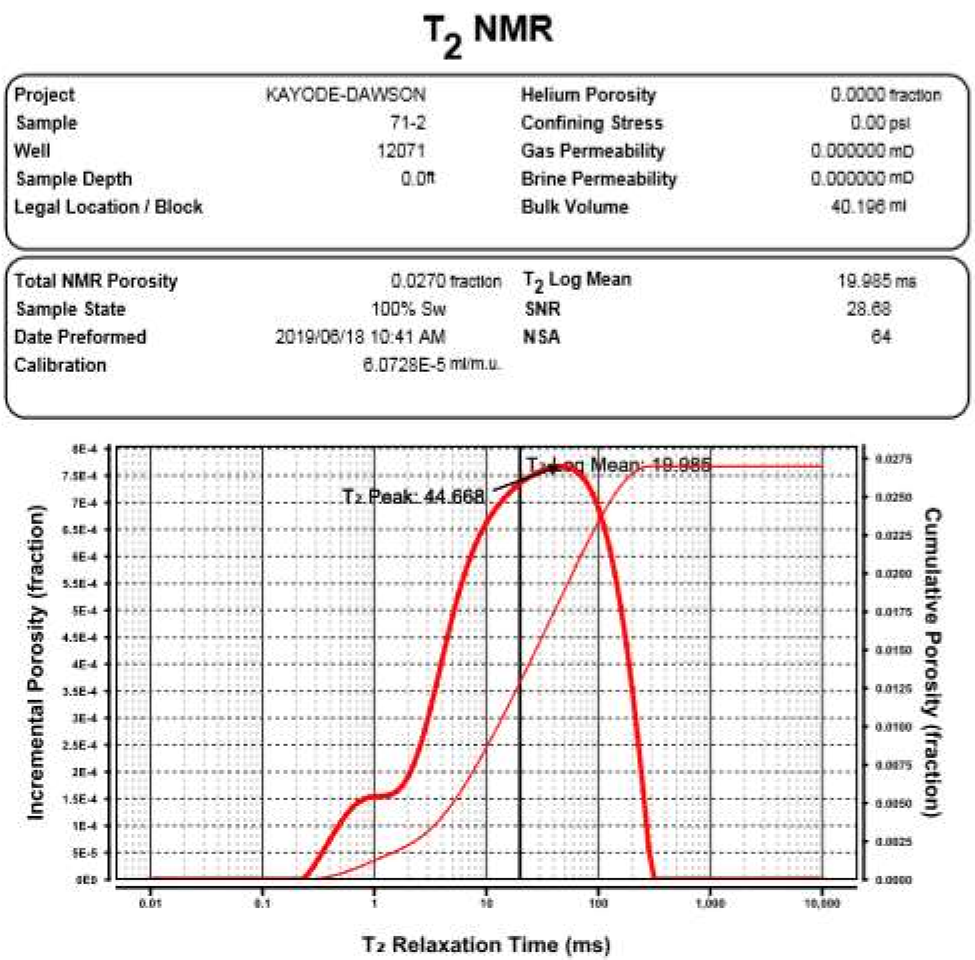


Fig. 33. T2 relaxation time graphs for core sample 71-2.

The incremental porosity (fraction) shows a slightly bimodal distribution of T2 relaxation times in core 71-2. There is no pronounced boundary between the incremental porosity of capillary bound fluid and free fluid in this sample. A noticeable shift to longer T2 relaxation times can be noted in this sample, and this is consistent across all the samples tested. Capillary bound water refers to the fluids in pores which are small enough to be bound to the pore surface by capillary forces and is represented here by the T2 relaxation times less than approximately 3 ms. The free fluid refers to the fluids in pores which are large enough to not be bound by capillary forces, so they are able to migrate out of the pore. The free fluid is represented here by T2 relaxation times greater than approximately 3 ms. This sample shows the capillary bound fluid and free fluid peaks representing unequal portions of the porosity with the highest T2 peak falling on the free fluid at 44.668 ms. There are more macropores than micropores and mesopores. The total NMR porosity fraction is 0.027.

Fig. 34 shows the T2 relaxation time graphs for core sample 71-3

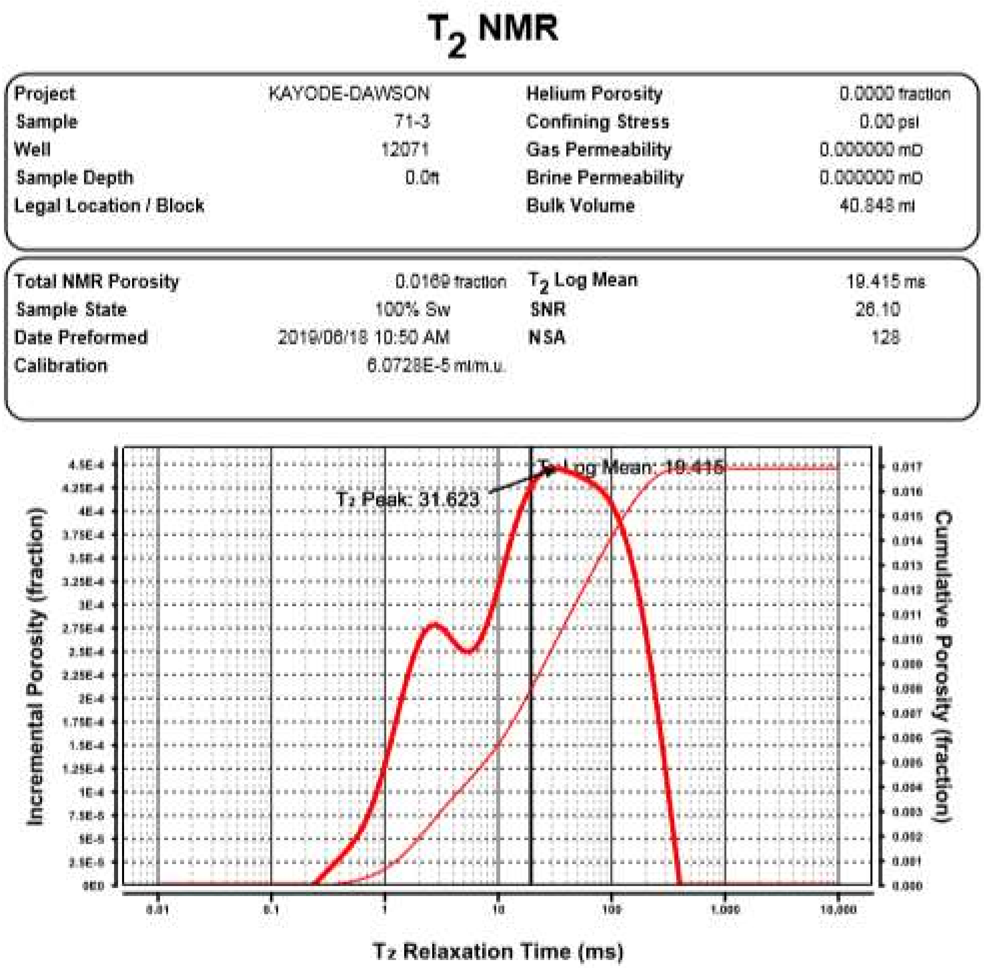


Fig. 34. T2 relaxation time graphs for core sample 71-3.

The incremental porosity (fraction) shows a bimodal distribution of T2 relaxation times in core 71-3. There is a slightly pronounced boundary between capillary bound fluid and free fluid in this sample. A noticeable shift to longer T2 relaxation times can be noted in this sample. Capillary bound water is represented here by the T2 relaxation times less than approximately 5 ms. The free fluid is represented here by T2 relaxation times greater than approximately 5 ms. This sample shows the capillary bound fluid and free fluid peaks representing unequal portions of the porosity with the highest T2 peak falling on the free fluid at 31.623 ms. There are more macropores than micropores in the sample. The total porosity fraction is 0.0169.

Fig. 35 shows the T2 relaxation time graphs for core sample 85-4

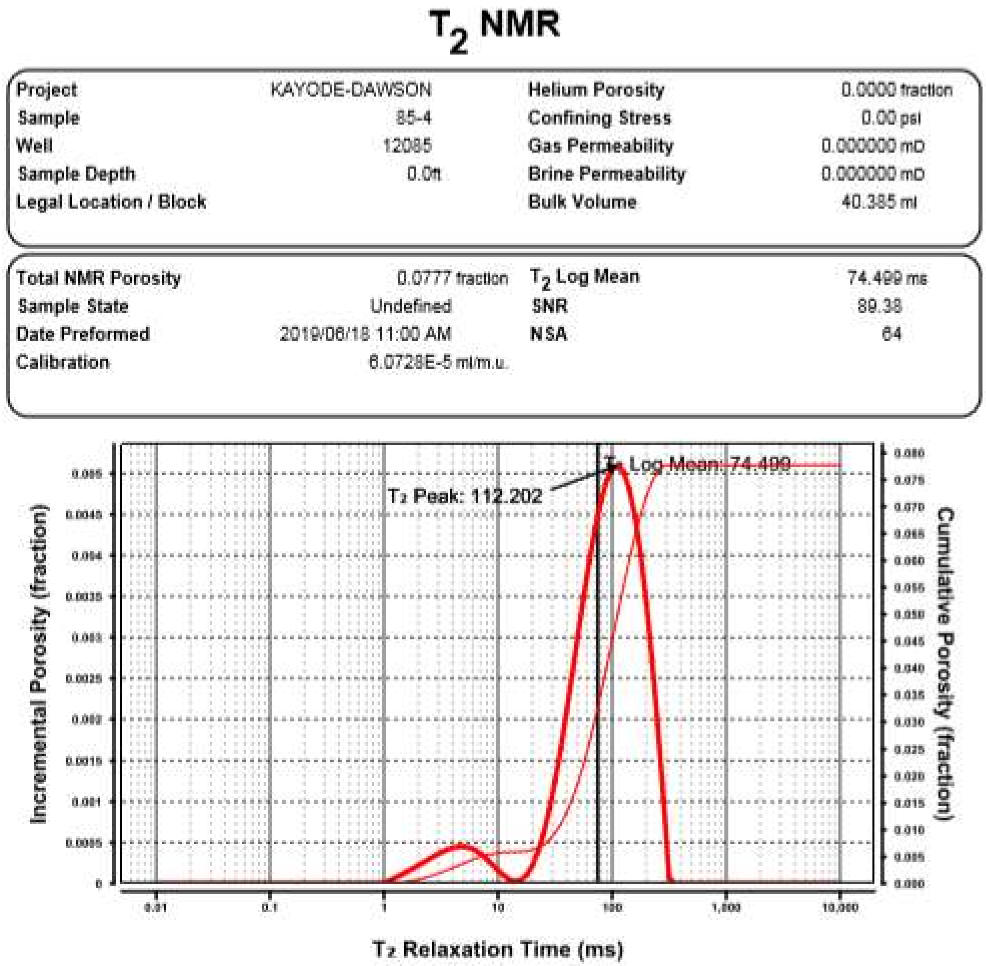


Fig. 35. T2 relaxation time graphs for core sample 85-4.

The incremental porosity (fraction) shows a bimodal distribution of T2 relaxation times of core 85-4. There is a boundary between capillary bound fluid and free fluid in this sample at approximately 11 ms. A noticeable shift to longer T2 relaxation times can be noted in this sample. The capillary fluid is represented here by T2 relaxation times less than 11 ms. The free fluid is represented here by T2 relaxation times greater than approximately 11 ms. This sample shows the capillary bound fluid and free fluid peaks representing unequal portions of the porosity with the highest T2 peak falling on the free fluid at 112.202 ms. There are more macropores than micropores and mesopores. The porosity fraction is 0.0777.

Fig. 36 shows the T2 relaxation time graphs for core sample 114-1.

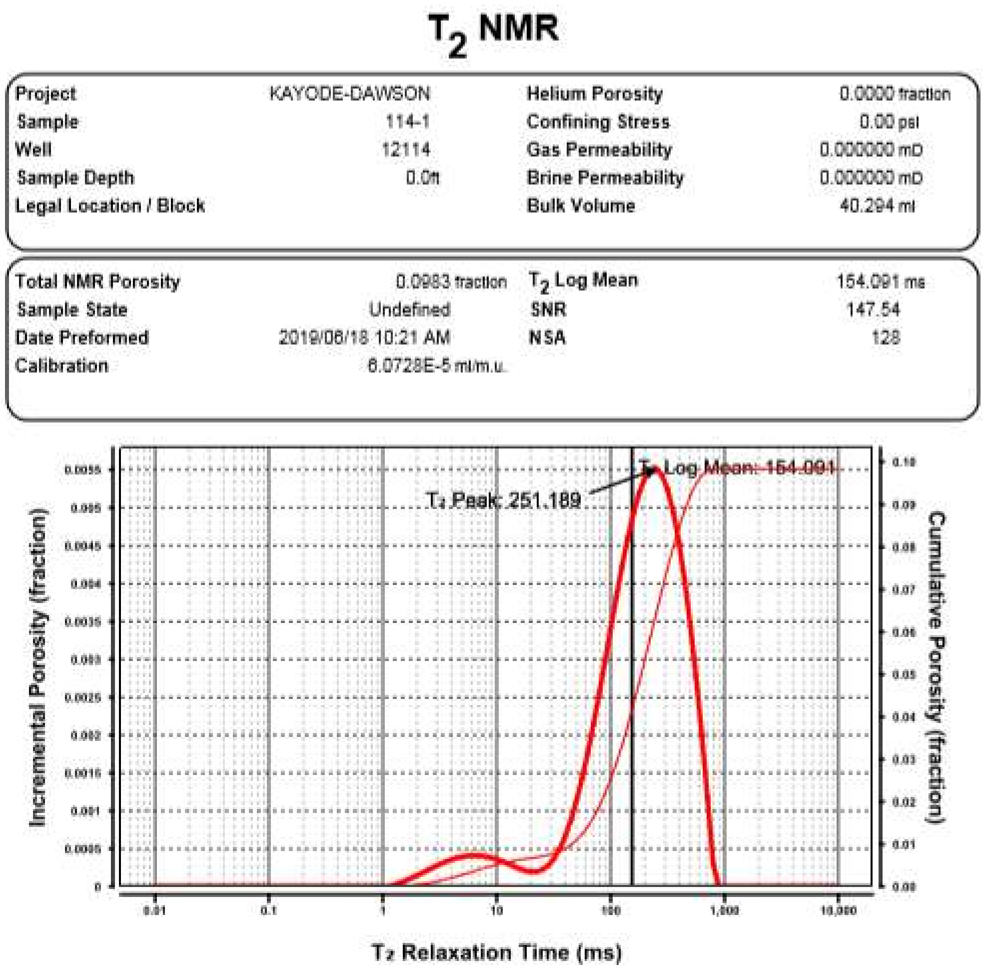


Fig. 36. T2 relaxation time graphs for core sample 114-1.

The incremental porosity (fraction) shows a bimodal distribution of T2 relaxation times of core 114-1. There is a boundary between capillary bound fluid and free fluid in this sample at approximately 11 ms. The capillary fluid is represented by T2 relaxation times less than 11 ms and the free fluid is represented here by T2 relaxation times greater than approximately 11 ms. This sample shows the capillary bound fluid and free fluid peaks representing unequal portions of the porosity with the highest T2 peak falling on the free fluid at 251.189 ms. There are more of macropores here. The total porosity fraction is 0.0983.

Fig. 37 shows the T2 relaxation time graphs for core sample 114-2

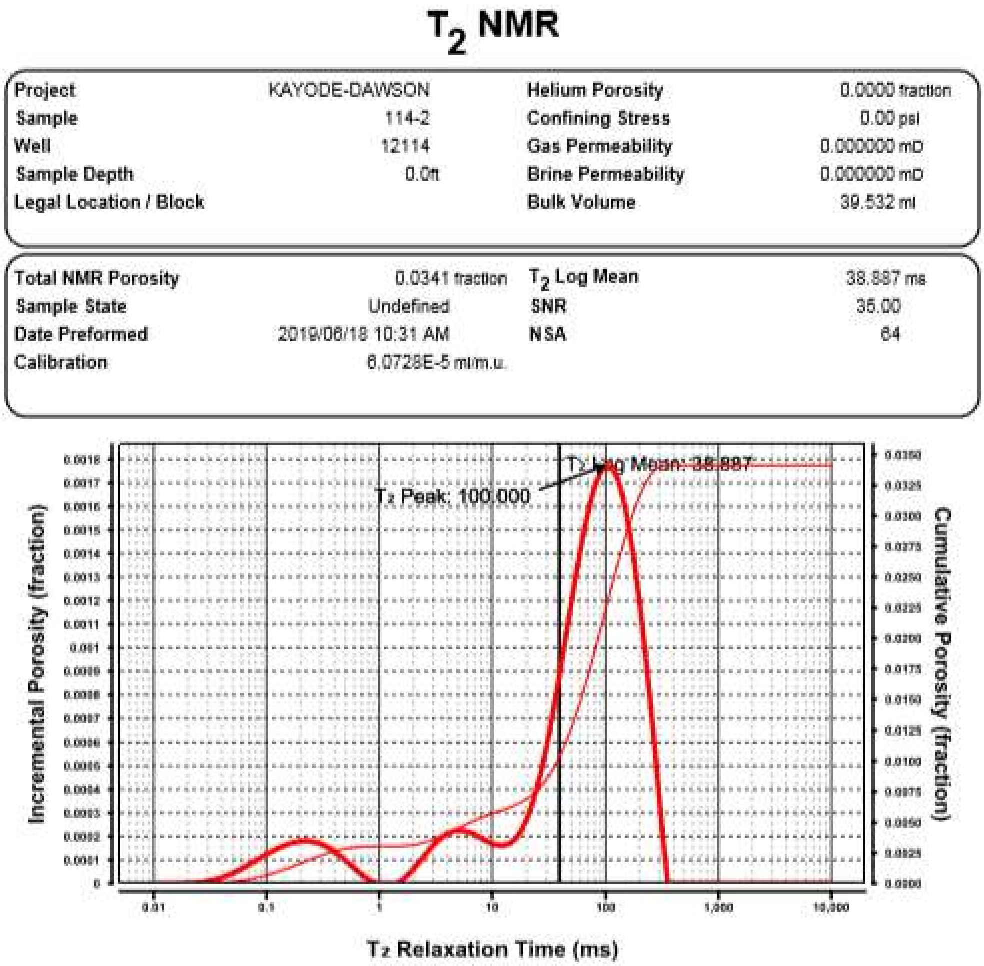


Fig. 37. T2 relaxation time graphs for core sample 114-2.

The incremental porosity (fraction) shows a bimodal distribution of T2 relaxation times of core 114-2. There are boundaries between seemingly clay bound fluid and capillary bound fluid, and between capillary bound fluid and free fluid in this sample at approximately 5 ms and 10 ms respectively. A noticeable shift to longer T2 relaxation times can be noted in this sample. Clay bound fluid is represented here by T2 relaxation times less than 1 ms, the capillary bound water is represented here by the T2 relaxation times between 1ms and 10 ms, and the free fluid is represented here by T2 relaxation times greater than approximately 10 ms. This sample shows the clay bound fluid, capillary bound fluid and free fluid peaks representing unequal portions of the porosity with the highest T2 peak falling on the free fluid at 251.189 ms. There are more macropores here. The total porosity fraction is 0.0341.

Fig. 38 shows the T2 relaxation time graphs for core sample 149-2.

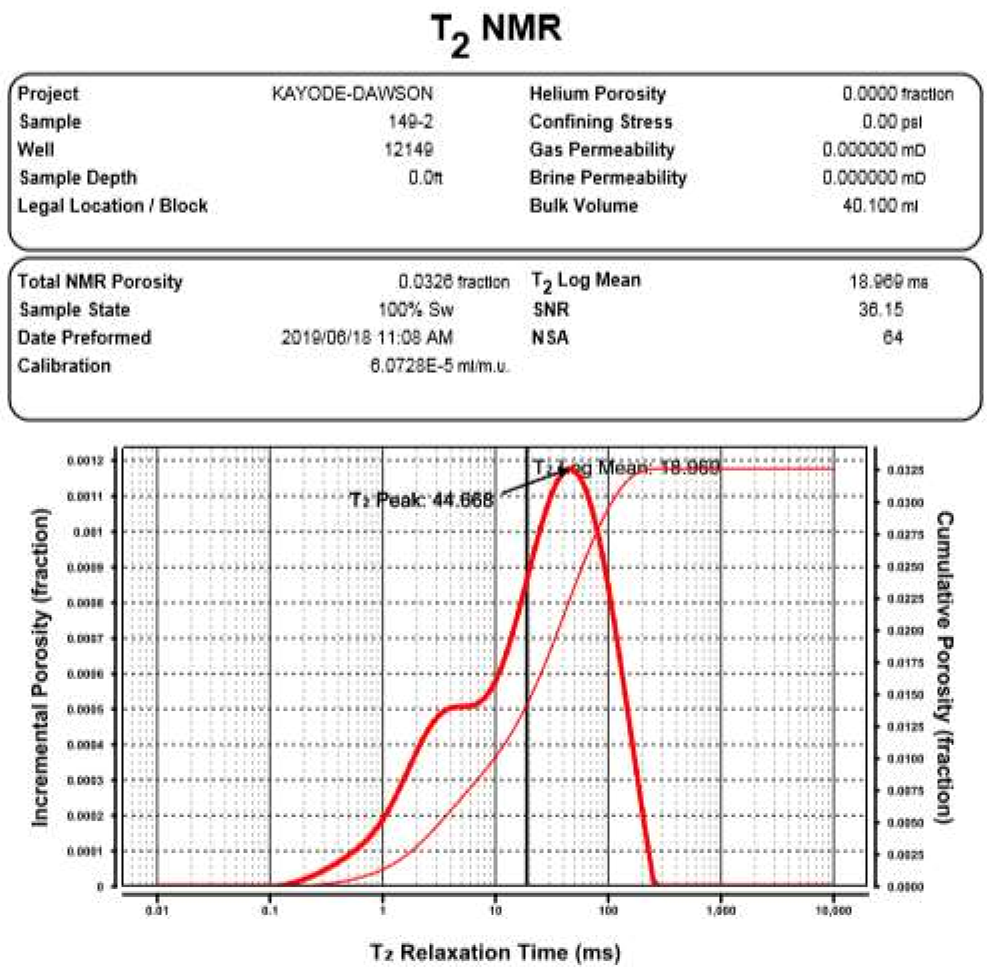


Fig. 38. T2 relaxation time graphs for core sample 149-2.

The incremental porosity (fraction) shows a bimodal distribution of T2 relaxation times core 149-2. This graph shows no pronounced boundary between the capillary bound water and the free fluid. Capillary bound water is represented here by the T2 relaxation times less than approximately 9 ms. The free fluid is represented here by T2 relaxation times greater than approximately 9 ms. This sample shows the capillary bound fluid and free fluid peaks representing unequal portions of the porosity with the highest T2 peak falling on the free fluid at 44.668 ms. The total porosity fraction is 0.0326.

Fig. 39 shows the T2 relaxation time graphs for core sample 149-3.

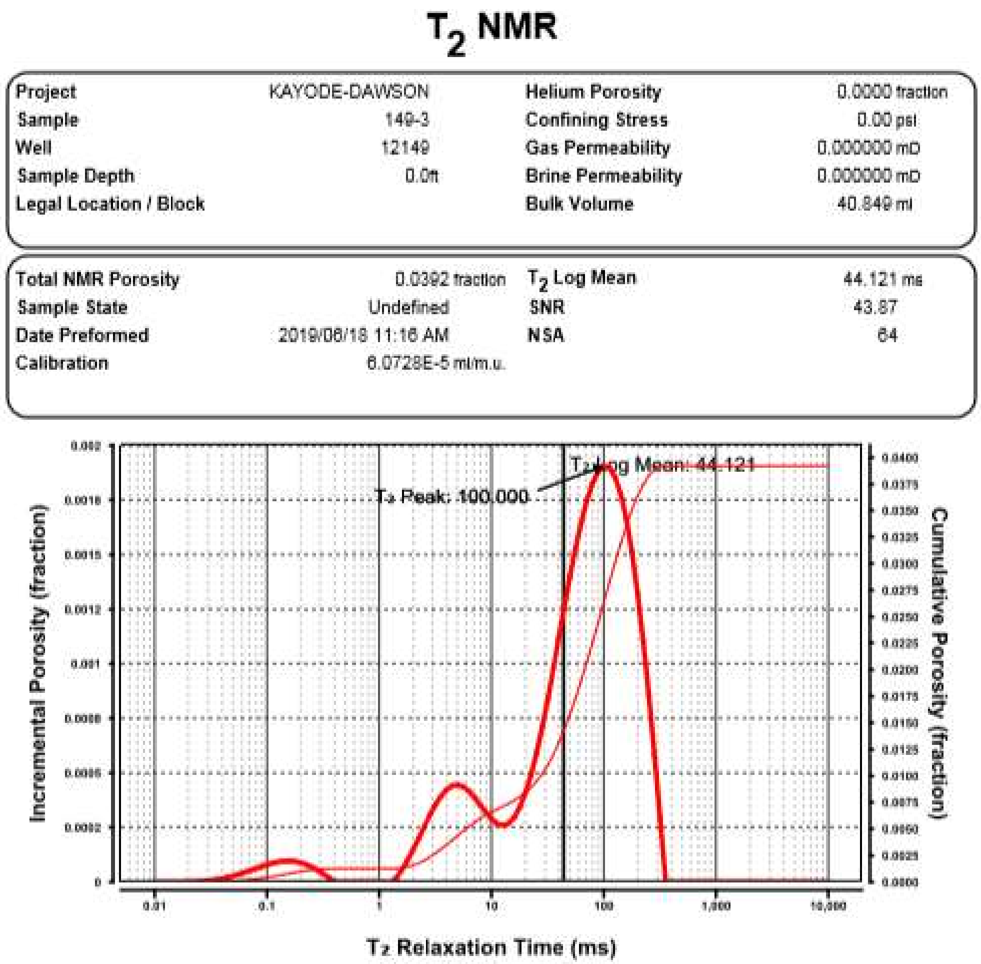


Fig. 39. T2 relaxation time graphs for core sample 149-3.

The incremental porosity (fraction) shows a bimodal distribution of T2 relaxation times of core 149-3. There is a boundary between clay bound fluid and capillary bound fluid, and between capillary bound fluid and free fluid in this sample at approximately 1ms and 11 ms respectively. A noticeable shift to longer T2 relaxation times can be noted in this sample. The clay bound fluid is represented by T2 relaxation times less than 1 ms, the capillary bound water is represented here by the T2 relaxation times less than approximately 11 ms and the free fluid is represented here by T2 relaxation times greater than approximately 11 ms. This sample shows the clay bound, capillary bound fluid and free fluid peaks representing unequal portions of the porosity with the highest T2 peak falling on the free fluid at 100.00 ms. There is also more of macropores here. The total porosity fraction is 0.0392.

Table shows the result of the porosity values obtained from the imbibition/weight methods and Nuclear Magnetic Resonance (NMR) methods.

Table 9. Result of Imbibition/ Weight method of Porosity and NMR Porosity values.

S/No	Core ID	Porosity-Imbibition/Weight method (Oil) (%)	Porosity-Imbibition/Weight method (Brine) (%)	Porosity-NMR (%)
1.	71-2	2.4877913	2.4877913	2.7
2.	71-3	2.4481174	2.4481174	1.69
3.	85-4	2.4758712	2.4758712	7.77
4.	114-1	2.4818244	2.4818244	9.83
5.	114-2	2.5308465	2.5308465	3.41
6.	149-2	2.4934671	2.4934671	3.26
7.	149-3	2.4476109	2.4476109	3.92

Correlation coefficient of porosity values from imbibition/weight method and porosity values from NMR method is 0.02.

The results do not correlate properly. The porosity values from NMR tests are higher than the values obtained from weight/imbibition methods tests. This may be attributed to the fact that the values from the NMR methods are from the absolute porosity while most values for weight/imbibition methods are from the effective porosity. These two set of values may not be related. The lower value of NMR porosity in core 71-3 may be attributed to probable plugging of some of the pores by salt crystals from the saturating brine.

The shape of the T2 relaxation graphs with more of macropores show the vuggy nature of the samples, which make the porosity to be heterogeneous.

4.3 Oil Properties

Table 10 shows the report of analysis of oil from Dawson Bay Formation in Dolphin Field.

Table 10. Report of Oil Analysis

Property	Value	Unit
API Gravity	42.2	@60 deg. F
Specific Gravity	0.8146	@ 60 deg. F
Pour Point	69	@ 60 deg. F
NaCl Content	44.5	LSB/1000 BBLS
Paraffin	16.37	% by weight
Sulfur	0.202	% by weight
Viscosity	2.53	Centistokes @ 100 deg. F
Viscosity	34.4	Saybolt universal seconds @ 100 deg. F
BS & W (Basic Sediment & Water)	3.2	%
BS & W	Trace	% sample analyzed

Source: Sathe Analytical lab, Williston (NDIC, 2018).

4.4 Aqueous Formulation Experiments

Table 11 shows the report of analysis of brine from Dawson Bay Formation in Dolphin Field.

Table 11. Brine Composition from Well 12085

	Mg/L	Meq./L
Cations		
Na+	78200.0	3401.5
Ca++	24490.0	1222.1
Mg++	2652.0	218.1
Iron	2.3	0.1
K+	3720.0	95.1
Barium	32.1	0.5
Chromium	0.8	0.0
Anions		
Chloride	177018.0	4993.5
Carbonate	0.0	0.0
Bicarbonate	158.7	2.6
Sulfate	400.9	8.3
Nitrate	63.9	1.0
pH	5.91	
NaCl	291899.1	Calc.

Source: Sathe Analytical lab, Williston (NDIC, 2018)

The base brine of 10% of the total dissolved solid (TDS) of the analyzed compositions was used to prepare different formulations.

Surfactant Formulation Test

The surfactant VX12279 was used. Different concentrations of surfactant and brine were prepared using the base brine and surfactant. The concentrations are by mass.

The results of the spontaneous imbibition tests are presented in this section.

Fig. 37 shows the typical cells of spontaneous imbibition.

Fig. 40. The Typical Cells of Spontaneous Imbibition

Figures 41-45 below show the result of spontaneous imbibition on the cores used for the experiment.

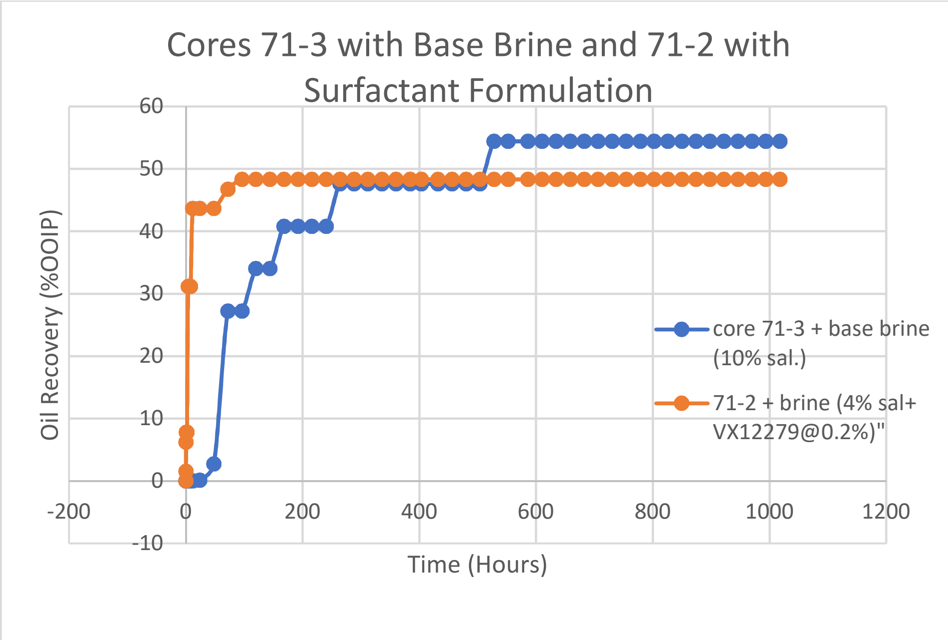


Fig. 41. Cores 71-3 with Base Brine and 71-2 with Surfactant Formulation

Fig. 41 shows that the rate of oil recovered from the core 71-2 in lower salinity and surfactant solution is faster in the first 200 hours than from the core 71-3 with base brine. It is also observed that the peak recovery was eventually higher in core 71-3. This may be due to higher permeability of core 71-3 (0.162 md) than core 71-2 (0.0403 md). This is in conformity with the findings of Wang et al. (2016), Olatunji et al. (2018), and it also shows that some other factors influence the recovery. The core 71-3 released more of Original Oil In Place (OOIP) than core 71-2.

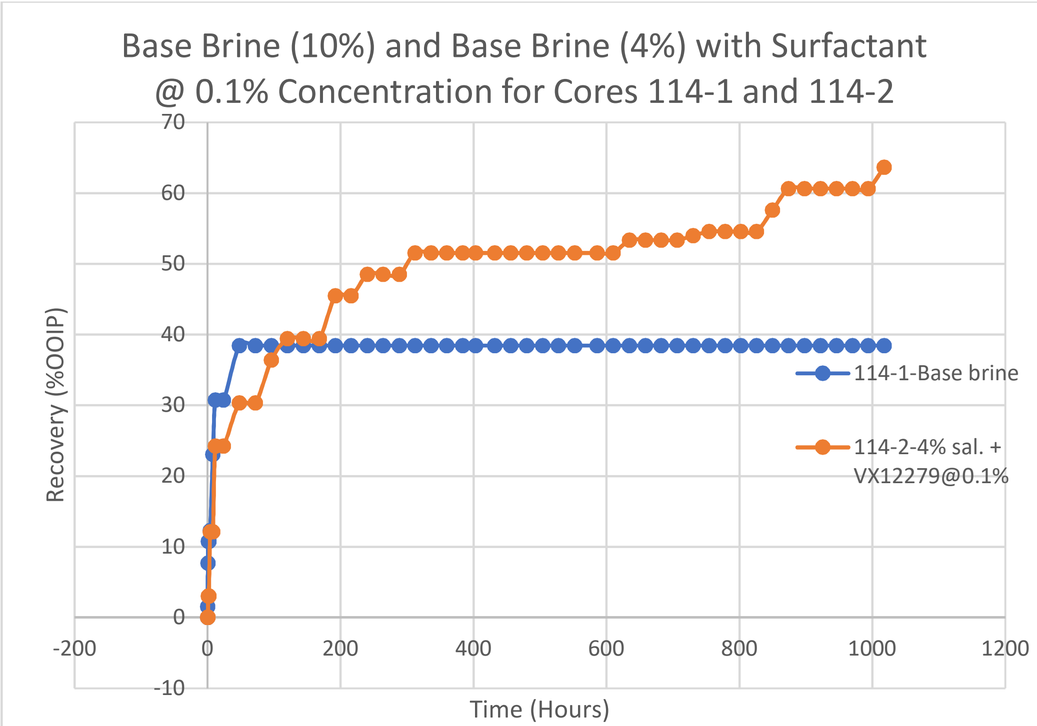


Fig. 42. Base Brine and Base Brine with Surfactant @ 0.1% Concentration for Cores 114-1 and 114-2

Fig. 42 shows that though core 114-1 in base brine (10% salinity) reached the peak recovery faster than core 114-2 in surfactant and less salinity (4% salinity with VX12279 @ 0.1%), the core 114-2 eventually has the highest oil recovery. Core 114-2 has higher permeability (0.143 md) and effective porosity (2.531) more than core 114-1(0.06 md and 2.482 respectively, and core 114-2 was also imbibed in lower salinity brine and surfactant compared to core 114-1.

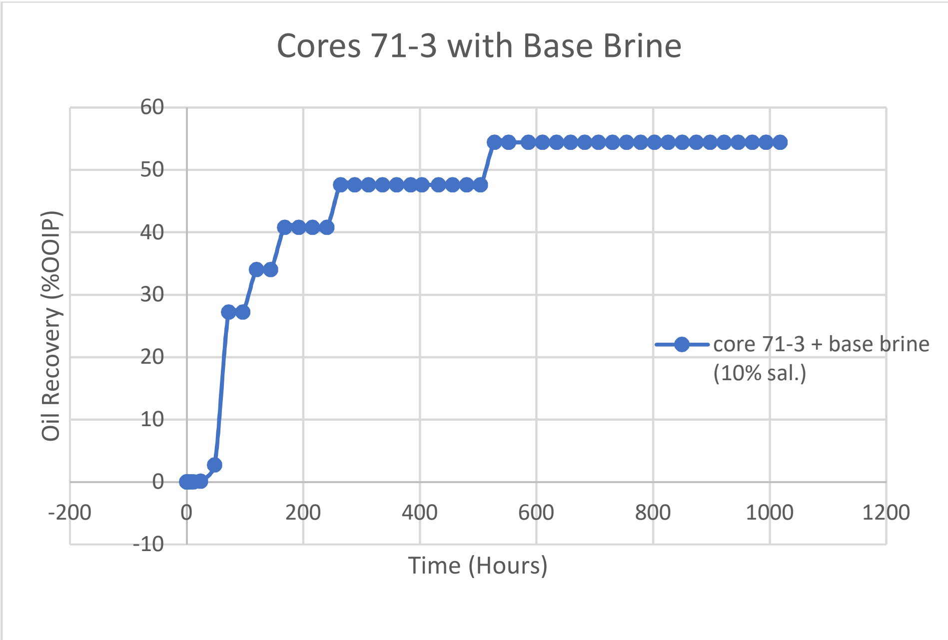


Fig. 43. Core 71-3 with Base Brine @ 10%

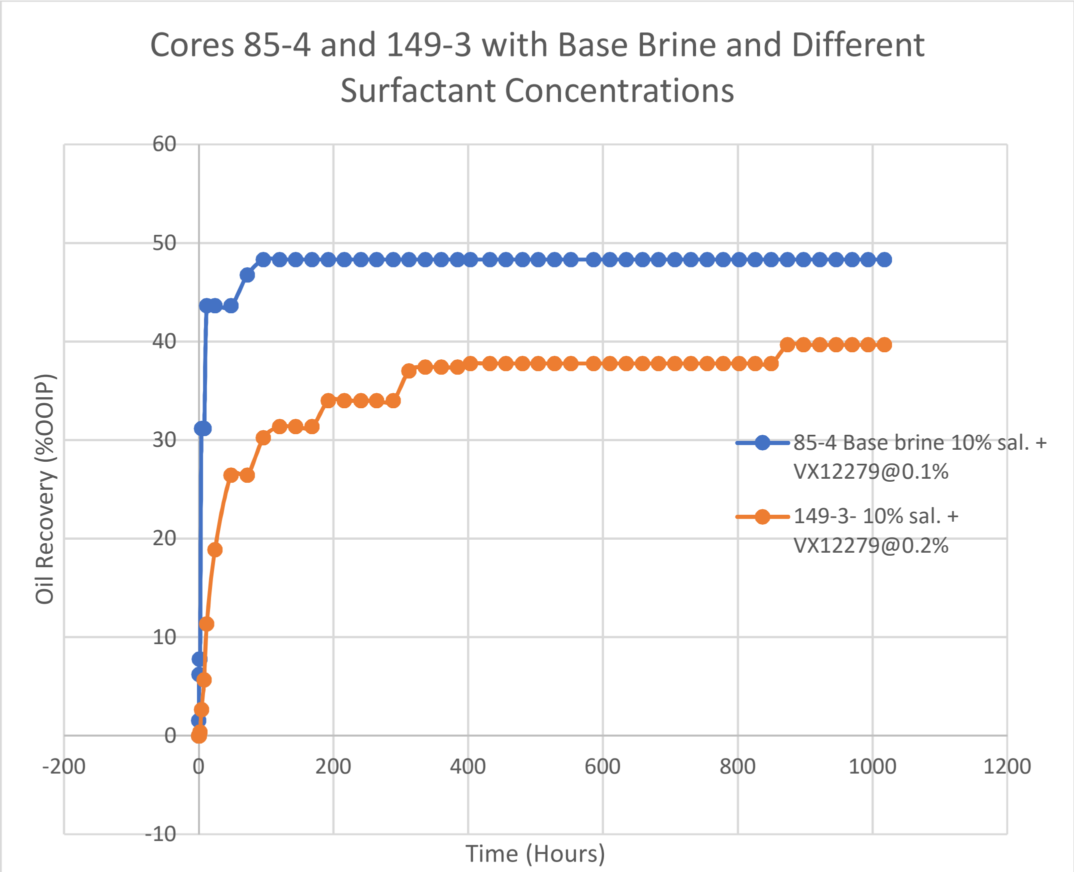


Fig. 44. Cores 85-4 and 149-3 with Base Brine and Different Surfactant Concentrations

Fig. 44 shows cores 85-4 and 149-3. Both cores are in solutions with the same brine salinity (10% salinity). The concentration of surfactant formulation was higher for core 149-3 (0.2%). Core 85-4 has permeability of 0.938 md while core 149-3 has permeability of 0.342 md. The higher recovery in core 85-4 may be attributed to relatively higher permeability.

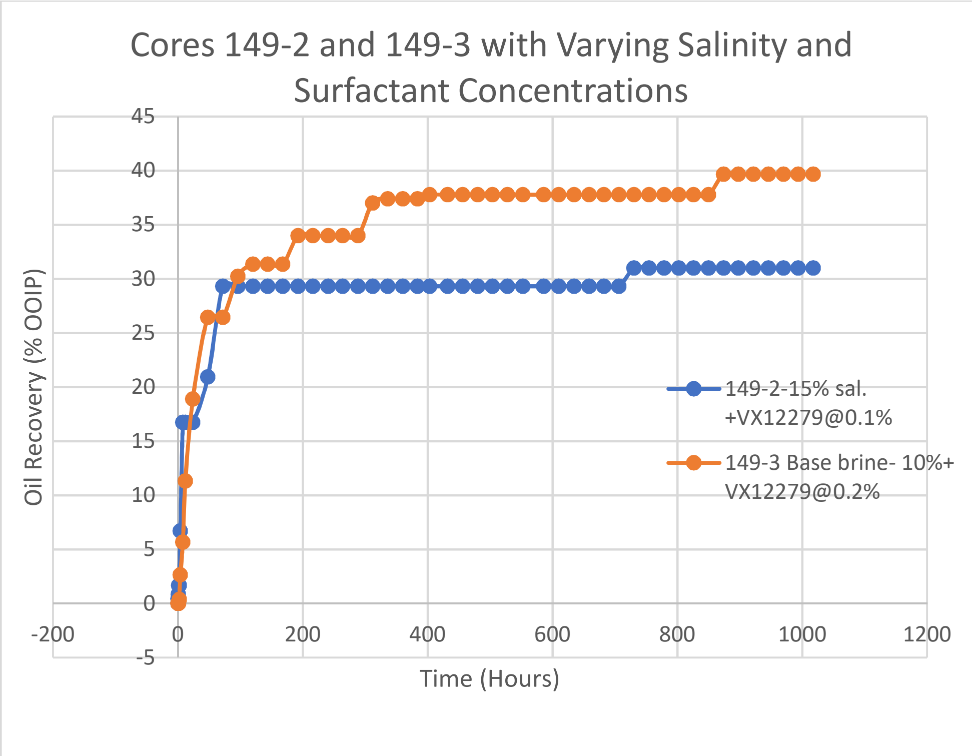


Fig. 45. Cores 149-2 and 149-3 with Varying Salinity and Surfactant Concentrations

Fig. 45 shows the cores 149-2 and 149-3. Core 149-3 was imbibed in a solution with lesser salinity and higher concentration of surfactant. The core in the solution with lesser salinity and more surfactant concentration yielded more oil than the other.

These results are in line with the results of Adibhatla, Sun and Mohanty (2005), Adibhatla and Mohanty (2006), Gupta and Mohanty (2007), and Gupta and Mohanty (2008) after carrying out a series of studies using anionic and nonionic surfactant to change the wettability of oil-wet fractured carbonate. They say that both anionic and nonionic surfactants gave results showing good potential for increasing oil recovery in a fractured limestone carbonate reservoir at 90°C. The carbonate cores used in the experiments in this report were not fractured but still gave good yield of recovery in varying degrees.

Table 12. The pH of Imbibition Solutions Before and After the Experiments

S/No	Max. Oil Recovery (%OOIP)/ Core	Surfactant	pH Before Imbibition	pH After Imbibition	Difference in pH
	48 /(71-2)	Base Brine (4% salinity) +VX12279 @ 0.2%	6.75	6.4	-0.35
	55/ (71-3)	Base Brine @ 10%	6.28	6.33	+0.05
	48/ (85-4)	Base Brine (10% salinity) + VX12279 @ 0.2%	6.58	5.9	-0.68
	32/ (114-1)	Base Brine (15% salinity) + VX12279@ 0.1%	6.33	5.8	-0.53
	48/ (114-2)	Base Brine (10% salinity) + VX12279 @ 0.1%	6.58	6.2	-0.38
	32 /(149-2)	Base Brine (15% salinity) + VX12279 @0.2%	6.46	5.89	-0.57
	40/ (149-3)	Base Brine (10% salinity) + VX12279@ 0.2%	6.55	5.69	-0.86

Table 10 shows that there is relative stability in pH values of the solutions before and after the spontaneous imbibition. This shows that the imbibition relatively did not change the acidity or alkanity of the imbibing solution.

4.5 Carbon Dioxide Flooding Experiments and Numerical Simulation

Experimental condition:

The conditions and procedure of the experiment is described below.

Saturated Mass of Core = 68.492 g

Confining Pressure = 4000 psi

Pump Volumes Before opening core bypass injection pump = 266.04 ml @ 3066 psi

Open injection pump valve with core bypass open

Weighing of the final mass after cooling down and disassembling of the hassler cell

Dry mass = 68.0873 g

Oil saturated mass = 68.492 g

Final mass = 68.2028 g

Mass of oil (Original Oil in place) = 0.4047 g

Oil Recovery within the period = $\frac{0.4047-(68.492-68.2028)}{68.492-68.0873}$ x 100 = $\frac{0.1155}{0.4047}$ x 100 = 28.54 % of the Original Oil in Place (OOIP)

This result agrees with the report of Habib et al. (2017) when they carried out Constant Composition Experiment tests on samples from Montney Tight Oil Play in the Western Canadian Sedimentary Basin using a PVT cell and visualization test. The visual test revealed that CO_2 can dissolve significantly in the oil and swell it causing oil recovery (Habibi et al., 2017).

Results of CO_2 'HnP' Numerical Simulation

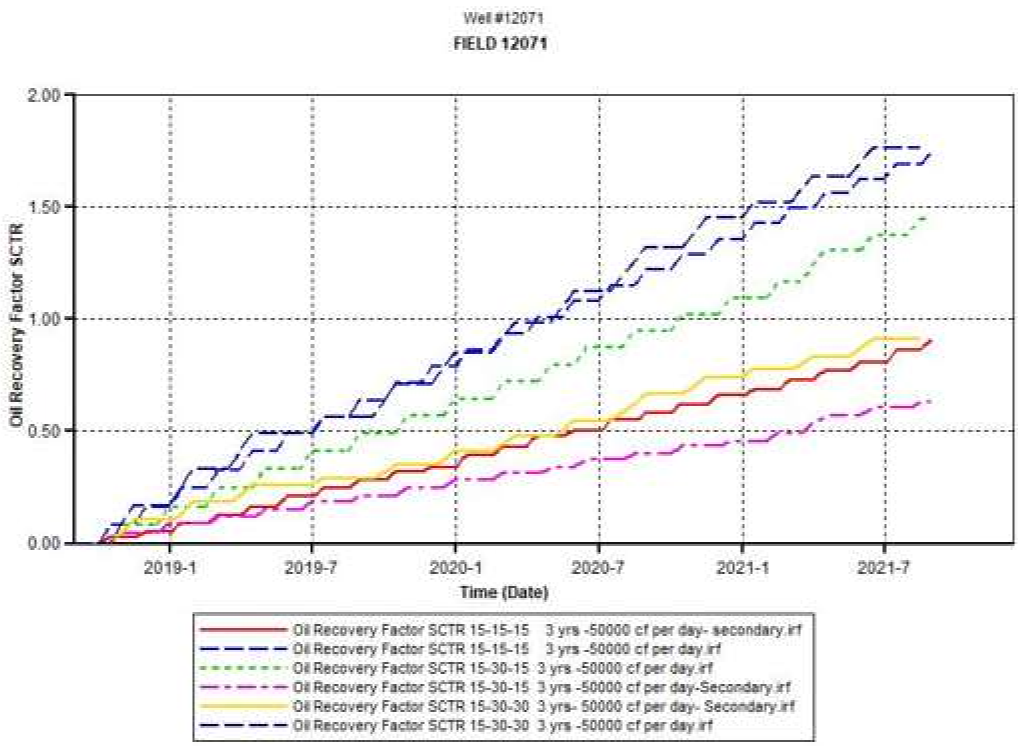


Fig. 46. Simulation result of 'CO_2 huff n puff' injection rate of 50000 cubic feet per day and water flooding for 3 years

The results for 'CO_2 huff n puff' shows the maximum recovery of about 1.75% by about July 2021 of (15-15-15) 15 days injection, 15 days imbibition (soaking) and 15 days production alternation. The simulation started on 31st of August 2018. 15-30-30 reached its highest recovery of about 1.7% at about August 2021. 15-30-15 recovery was at the lowest rate, reached the peak of about 1.4% by about August 2021. Similarly, in water flooding (secondary recovery) 15-30-30 rose along with 15-15-15, reached about 0.8%, 15-15-15 reached the maximum peak of about 0.8% on August 2021, 15-30-15 reached about 0.6% on August 2021.

It can be inferred that 15-15-15 and 15-30-15 give the optimum alternation for this field. The tertiary CO_2 recovery is higher than secondary water flooding for each case in the field

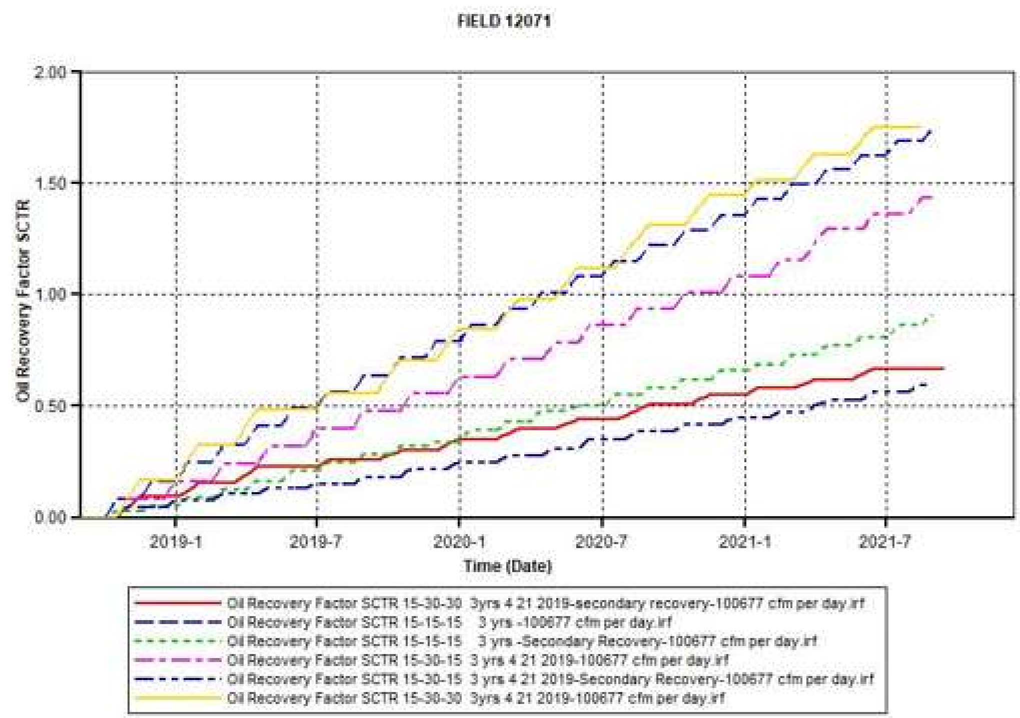


Fig. 47. Simulation result of 'CO_2 huff n puff' injection rate of 100677 cubic feet per day and water flooding for 3 years

The results for CO_2 flooding show the 15-15-15 and 15-30-30 reaching the peak of about 1.7% on August 2021, and 15-30-15 attaining the peak of about 1.4 % on July 2021. 15-30-30 competed steadily with 15-15-15 and reached the peak together on August 2021. The secondary recovery for 15-15-15 reached the peak of about 0.85%, 15-30-15 reached the peak of about 0.55%, and 15-30-30 reached about 0.65% in September 2021.

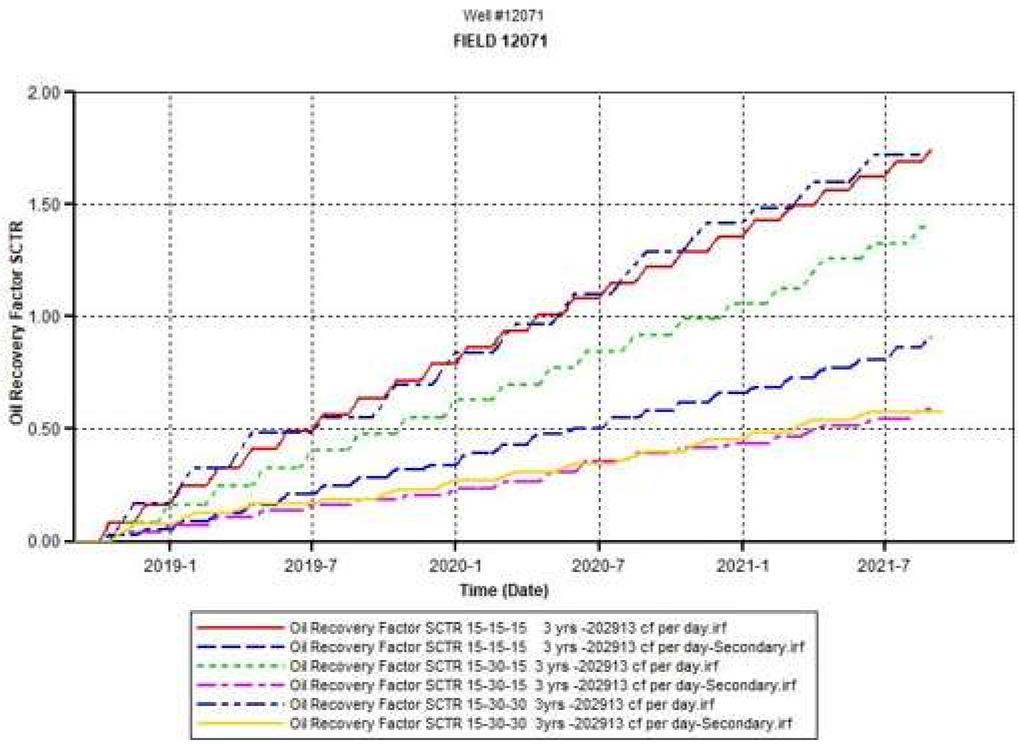


Fig. 48. Simulation result of 'CO_2 huff n puff' injection rate of 202913 cubic feet per day and water flooding for 3 years

Fig. 48 shows that for 'CO_2 huff n puff', 15-15-15 and 15-30-30 reached the peak of 1.65% in August 2021, 15-30-15 reached the peak of about 1.4% in August 2021. The secondary recovery stopped at the same respective time for CO_2 flooding, 15-15-15 reached 0.8% by August 2021, 15-30-15 and 15-30-30 reached 0.55%.

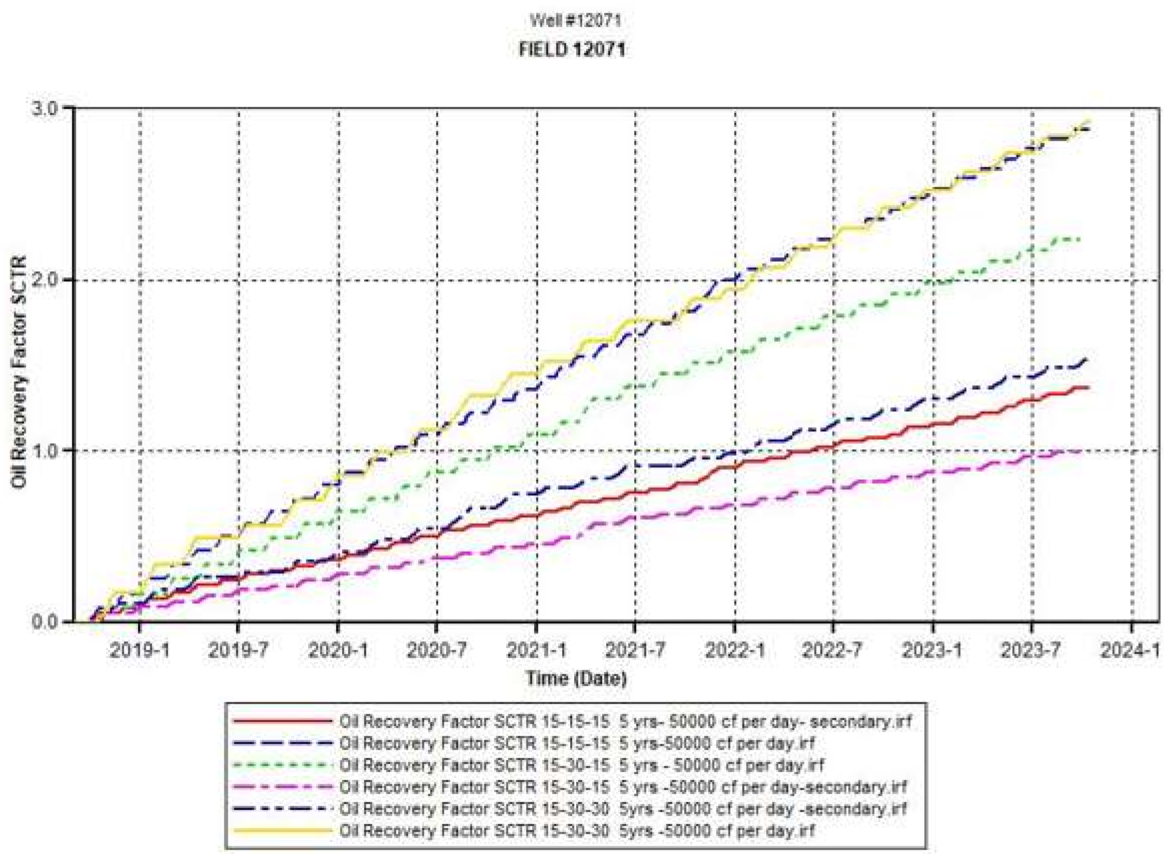


Fig. 49. Simulation result of ‘CO_2 huff n puff’ injection rate of 50000 cubic feet per day and water flooding for 5 years

Fig. 49 shows that for ‘CO_2 huff n puff’, 15-15-15 and 15-30-30 rose comparatively, reached about 2.8% in August 2023, 15-30-15 reached about 2.3% in August 2023. Secondary recovery shows 15-30-30 reaching 1.5% at August 2023. 15-15-15 reached 1.3%, and 15-30-15 reached 1.0 %, all in August 2023.

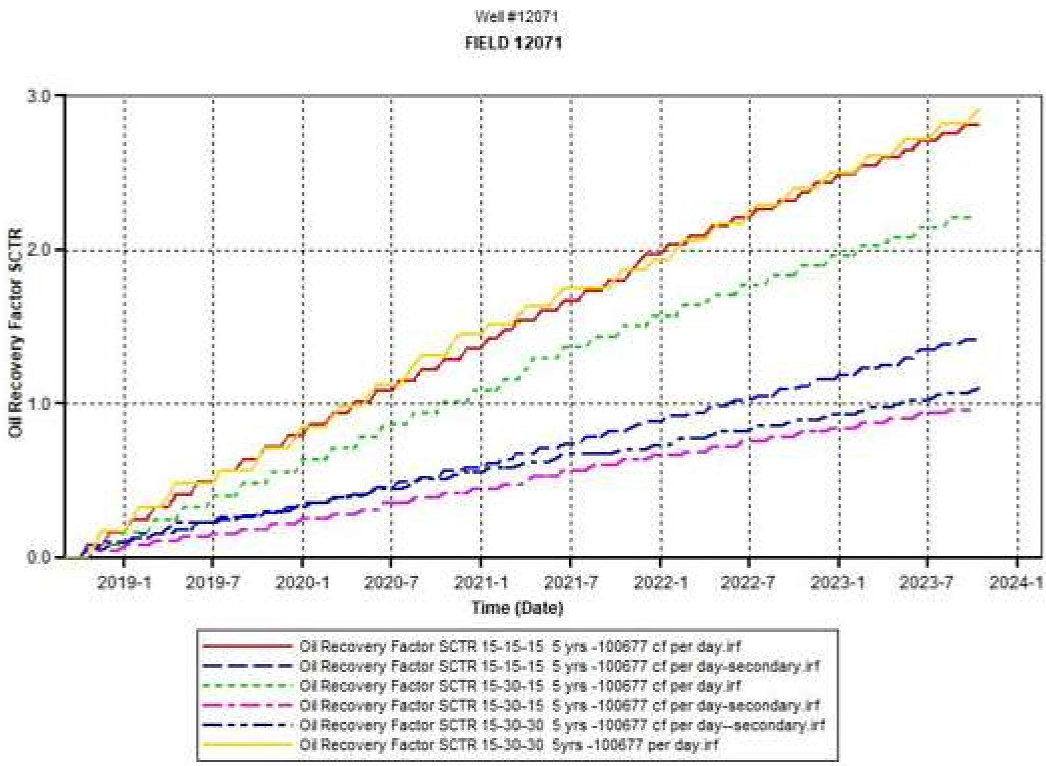


Fig. 50. Simulation rate of 'CO_2 huff n puff' injection rate of 100677 cubic feet per day and water flooding for 5 years.

Fig. 50 shows for 'CO_2 huff n puff', 15-15-15 and 15-30-30 reaching 2.8% in August 2023, 15-30-15 reached 2.3% in April 2023. Secondary flooding shows that for 15-15-15 it reached 1.4 %, 15-30-30 reached 1.1%, and 15-30-15 reached 0.9%, all in August 2023.

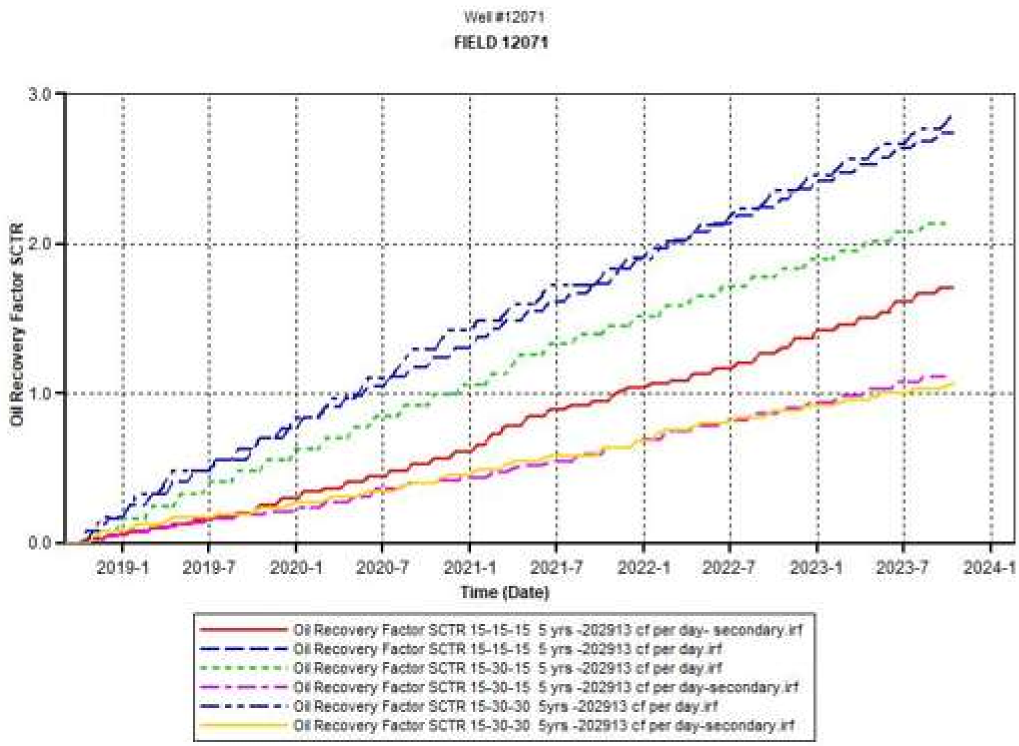


Fig. 51. Simulation result of 'CO_2 huff n puff' injection rate of 202913 cubic feet per day and water flooding for 5 years

Fig. 51 shows that for 'CO_2 huff n puff', 15-15-15 and 15-30-30 reached 2.8% in August 2023, 15-30-15 reached 2.2% by August 2023. The secondary recovery, waterflooding shows that by August 2023, for 15-15-15 the oil recovery reached 1.7%, 15-30-15 reached 1.1%, and 15-30-30 reached 1.1%.

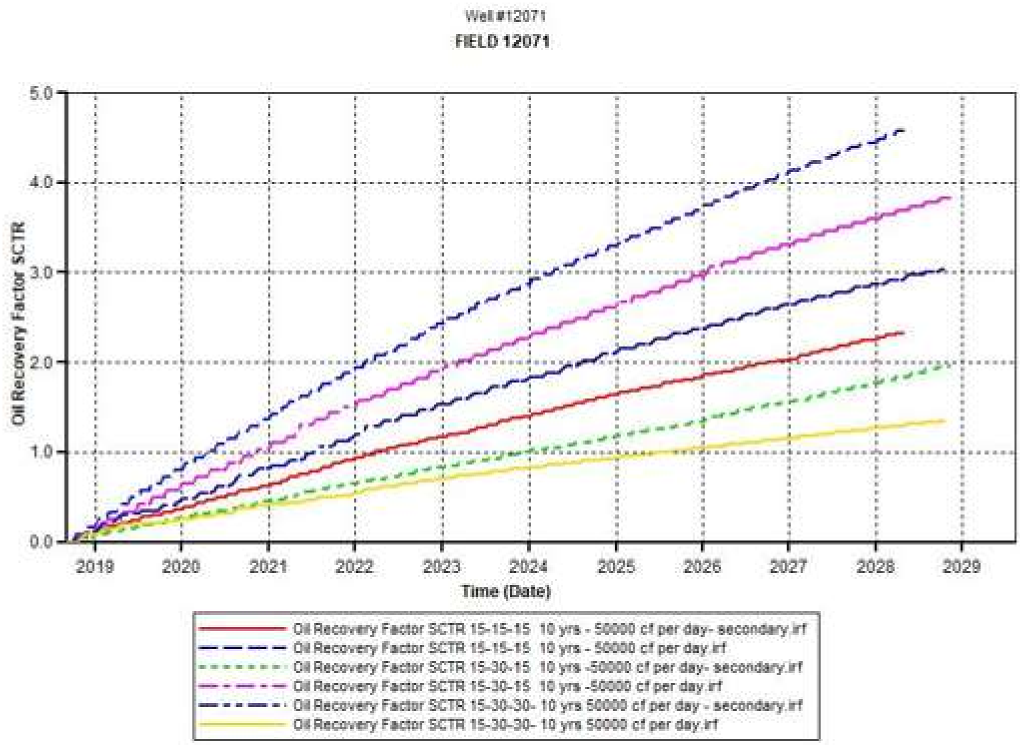


Fig. 52. Simulation result of 'CO_2 huff n puff' injection rate of 50000 cubic feet per day and water flooding for 10 years

Fig. 52 shows that for 'CO_2 huff n puff', in 15-15-15, the oil recovery reached 4.7% by 2028, 15-30-15 reached 3.8% on August 2028, 15-30-30 reached 3.0% on August 2028. Secondary recovery shows that for 15-15-15, 2.3% was reached, 15-30-15, 1.8% was reached, 15-30-30 reached 1.2%, by 2028.

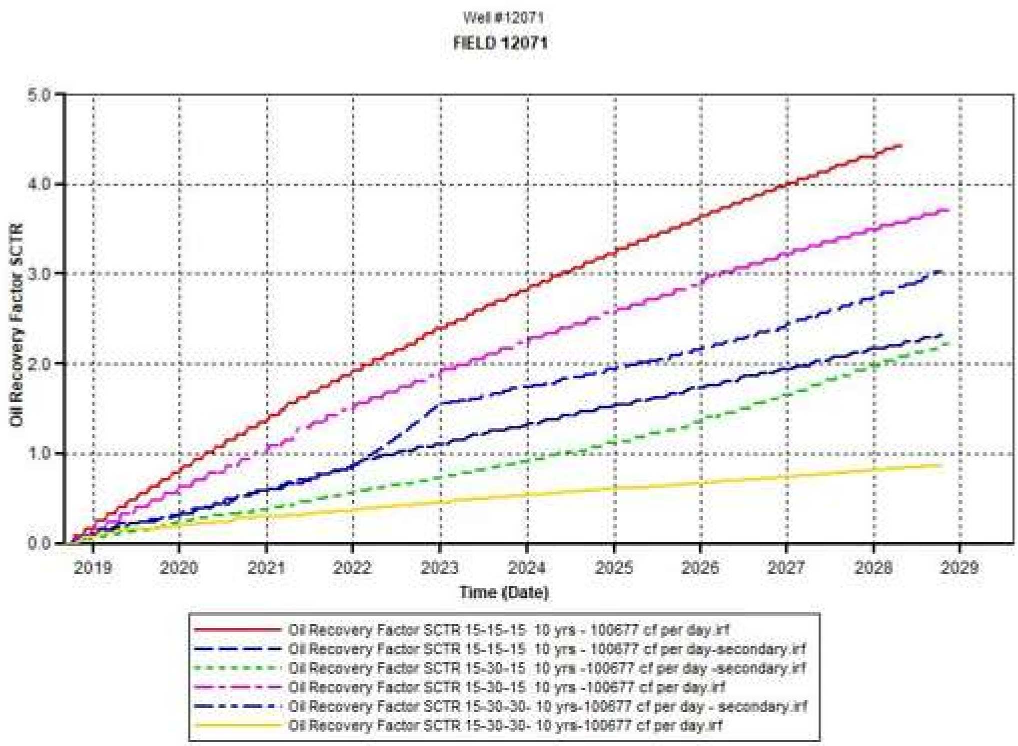


Fig. 53. Simulation result of ‘CO_2 huff n puff’ injection rate of 100677 cubic feet per day and water flooding for 10 years.

Fig. 53 shows that for CO_2 recovery, 15-15-15 reached 4.5% in 2028, 15-30-15 reached 3.6% in 2028, 15-30-30 reached 2.8% in 2028. The secondary recovery has the same ending time as in previous cases, 15-15-15 reached 2.3%, 15-30-30 reached 2.1% and 15-30-30 reached 0.9%, all after 10 years.

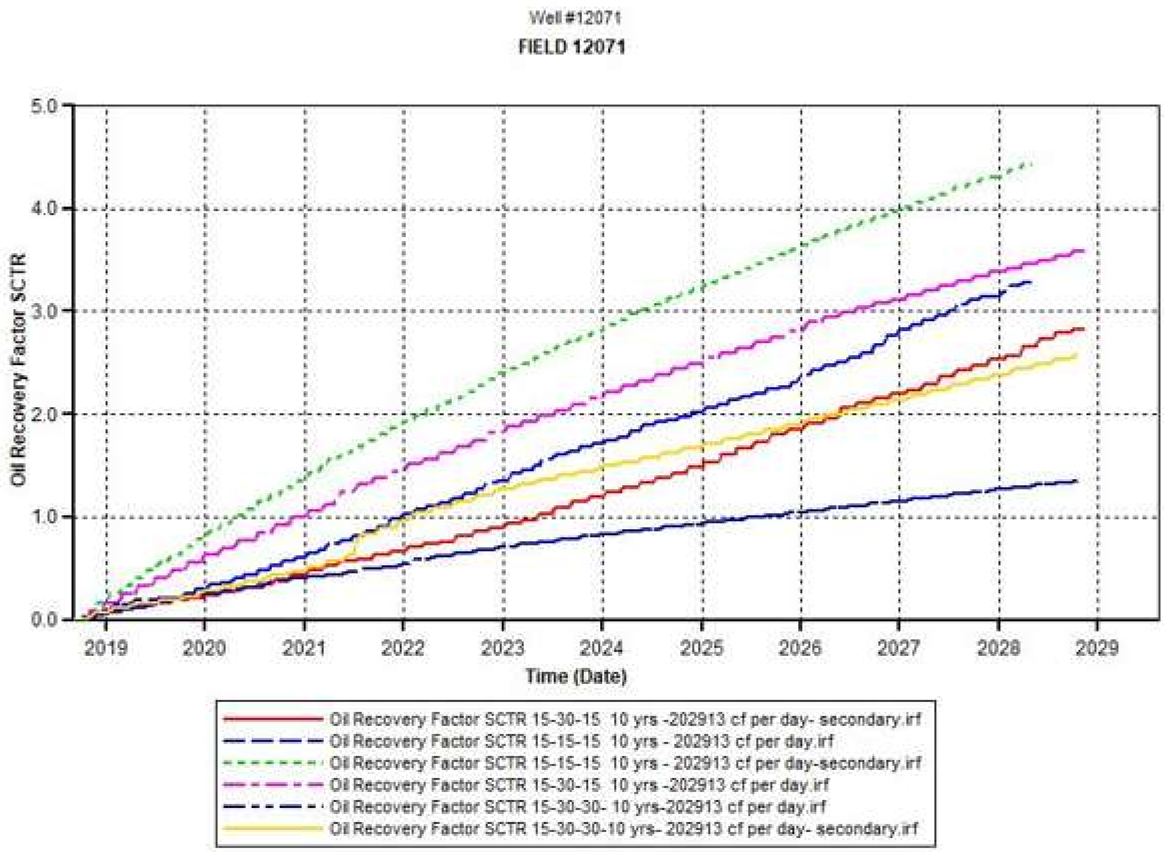


Fig. 54. Simulation result of 'CO_2 huff n puff' injection rate of 202913 cubic feet per day and water flooding for 10 years

Fig. 58 shows that for CO_2 recovery, 15-15-15 reached 4.4% in 2028, 15-30-15 reached 3.5% in 2028. 15-30-30 reached 3.2% in 2028. The secondary recovery shows that 15-15-15 reached 2.5% by in 2028, 15-30-15 reached 2.6% and 15-30-30 reached 1.3%, all at the same time in 2028.

Summary and Inferences

The longest time of oil recovery simulated is 10 years. The longer the number of years, the more the oil recovery for both tertiary CO_2 'HnP' and secondary recoveries. In tertiary recoveries, modes 15-15-15 and 15-30-30 compete favorably and yield almost the same recoveries at 3 years and 5 years but at 10 years, 15-15-15 yielded more. Generally, 15-30-30 yields more than 15-30-15 in secondary recoveries. The tertiary (CO_2 'HnP') recoveries are more than secondary (water flooding) in each case. Modes influence the percentage of recoveries more than the volume rate of fluid injected. The highest recovery of the whole simulation is for CO_2 'huff n puff' at 15-15-15 modes for 10 years.

It can be inferred that the optimum soak period is 15 days from the options tried in the simulation. It is important to determine the optimum soak period, because the maximum incremental oil recovery ultimately requires a soak period (Monger and Coma, 1988). The highest 'huff n puff' recovery is at 15-15-15 modes for 10 years and the value is 4.7%.

The result of the numerical simulation shows that CO_2 'huff n puff' process which involves injection of CO_2 into the reservoir at certain pressure, the injection wells then being shut in to allow the soaking for a period before the wells are switched to production wells (Song and Yang, 2013) can be a good process of oil recovery in the Dawson Bay Formation of Dolphin Field as Haskin and Alston (1989) say.

Table 13. Petrophysical Properties of the Cores and Properties of the Oil Used for the Experiments and EOR Method Screening

Well No	Sampling Core ID	Rock type	Porosity (%)	Avg. Permeability (md)	Oil Saturation (%)	Depth (ft.) MD	Net Thickness (on field)	Temp.	API Gravity of Oil	Viscosity of Oil	Oil Composition	S.G of Oil	Recommended EOR Method (Taber et al., 1997)
12071	71-2	Dolomite	2.4877913	0.0403	100	9924.5	Wide Range	221F	23.65 @ 70 deg F	4.5 @ 70 deg F	27.22 % of paraffin by mass	0.912 @ 70 deg F	CO_2; Micellar/Polymer ASP and Alkaline Flooding
12071	71-3	Dolomite	2.4481174	0.162	100	9930	Wide Range	221 F		4.5 @ 70 deg F	As above	0.912 @ 70 deg F	CO_2; Micellar/Polymer ASP and Alkaline Flooding
12085	85-1	Dolomite	2.1885787	0.243	100	9922	Wide Range	221 F	23.65 @ 70 deg F	4.5 @ 70 deg F	As above	0.912 @ 70	CO_2; Micellar/Polymer ASP and Alkaline Flooding

												deg F	
12085	85-4	Dolomite	2.47587 12	0.938	100	10006.4	Wide Range	221 F	23.65 @ 70 deg F	4.5 @ 70 deg F	As above	0.912 @ 70 deg F	CO_2; Micellar/Polymer ASP and Alkaline Flooding
12114	114-1	Dolomite	2.48182 44	0.06	100	9953.7	Wide Range	221 F	23.65 @ 70 deg F	4.5 @ 70 deg F	As above	0.912 @ 70 deg F	CO_2; Micellar/Polymer ASP and Alkaline Flooding
12114	114-2	Dolomite	2.53084 65	0.143	100	9956.5	Wide Range	221 F	23.65 @ 70 deg F	4.5 @ 70 deg F	As above	0.912 @ 70 deg F	CO_2; Micellar/Polymer ASP and Alkaline Flooding
12149	149-2	Dolomite	2.49346 71	0.262	100	10081.7	Wide Range	221 F	23.65 @ 70 deg F	4.5 @ 70 deg F	As above	0.912 @ 70 deg F	CO_2; Micellar/Polymer ASP and Alkaline Flooding
12149	149-3	Dolomite	2.44761 09	0.342	100	10069.3	Wide Range	221 F	23.65 @ 70 deg F	4.5 @ 70 deg F	As above	0.912 @ 70 deg F	CO_2; Micellar/Polymer ASP and Alkaline Flooding

Table 14. Typical EOR Screening for Reservoir of Dawson Bay Formation, Dolphin Field, Divide County, North Dakota, US.

Well No.	Rock Type	Por.	Avg. Permeability (md)	Oil Saturation (%)	Depth (ft.) MD	Net Thickness	Temp.	API Gravity	Viscosity	S.G	Recommended EOR Method (Taber et al., 1997)
*12071	Carbonate(Dolomite)	0.5-8.7	0.01-43	0-34.6	9919.2-10081.7	Wide Range	220-236 F	37.1 @60 deg F	4.28 CS@100 deg F; 40.1 SUS@100 deg F	0.8393@60 deg F	CO_2; Micellar/Polymer ASP and Alkaline Flooding

*Data from NDIC well files

Table 15. EOR Screening Criteria by Taber et al. (1997).

	Oil Properties			Reservoir Characteristics					
EOR Methods	Gravity (°API)	Viscosity (cp)	Composition	Oil Saturation (% p.v.)	Formation Type	Net Thickness (ft.)	Avg. Permeability (md)	Depth (ft.)	Temperature (°F)
Gas Injection Methods (Miscible)									
Nitrogen and Flue Gas	>36 48	<0.4 0.2	High percent of C_1 to C_7	>40 75	Sandstone or Carbonate	Thin unless Dipping	NC	>6000	NC
Hydrocarbon	>23 41	<3 0.5	High percent of C_2 to C_7	>30 80	Sandstone or Carbonate	Thin unless Dipping	NC	>4000	NC
CO_2	>22 36	<10 1.5	High percent of C_2 to C_7	>20 55	Sandstone or Carbonate	Wide Range	NC	>2500	NC
Immiscible Gases	>12	<600	NC	>35 70	NC	NC if dipping and/or good vertical permanently	NC	>1800	NC

Enhanced Waterflooding									
Micellar/Polymer, ASP and Alkaline Flooding	>20 35	35 13	Light Intermediate Some organic acids for alkaline floods	>35 53	Sandstone preferred	NC	>10 450	>9000 3250	200 80
Polymer Flooding	>15	<150 > 10	NC	>50 80	Sandstone preferred	NC	10 800	<9000	200 140
Thermal/Mechanical									
Combustion	>10 16 to ?	<5000 to 1200	Some asphaltic components	50 72	High porosity Sandy Sandstone	>10	>50	<11500 3500	>100 135
Steam	>8 to 13.5 to ?	<200,000 to 4700	NC	>40 66	High porosity Sandy Sandstone	>20	>200 2540	<4500 1500	NC
Surface mining	7 to 11	Zero cold flow	NC	>8 wt% Sand	Mineable Tar sand	>10°	NC	>3:1 Overburden to sand ratio	NC

Taber et al. (1997).

NC- not critical

4.6 Comparison of Results of Enhanced Oil Recovery Potential

Considering Taber et al. (1997) the oil properties and reservoir properties of the Dawson Bay Formation of Dolphin Field, all criteria except reservoir permeability fit into CO_2 and ASP flooding EOR methods recommendation.

The surfactant imbibition experiments show recovery of up to 64%, the brine of up to 54% and CO_2 flooding yielded 28.54 % oil recovery. The numerical simulation yielded 4.7% (after 10 years) as the highest of 'CO_2 'HnP' for the formation, the lower value compared to laboratory value can be attributed to the complexity of the formation reflected in the numerical simulation which is not expressed in the cores in the laboratory experiments. At the laboratory and simulation scale, Dawson Bay Formation in Dolphin Field is amenable to Surfactant and CO_2 methods of enhanced oil recovery. These methods are recommended by Taber et al. (1997) for the formation which has the reservoir with petrophysical properties and oil properties like the one established to be in this field studied.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The thickness of the reservoir rock, predominantly dolomite, slightly limestone, thickens from about 10 ft to about 100 ft. It's thick at the mid-eastern part of the field and thins sideways. This may likely suggest the topography of the marine environment where the limestone was deposited before it was characterized for hydrocarbon accumulation or variability in diagenesis. The oil producing wells are on Nesson Anticline, the reservoir trap has a structural element. There is no clear closure seen on the structure of the field, reservoir trap may be attributed to halite plugs in the dolomite rock, making it more stratigraphic than structural.

The petrophysical properties of the formation values show deviation of values from log analysis to be different for values from core analysis. The correlation value was also too low for a reliable relationship. The correlational coefficient for depth 9917 to 9932 ft with 0.5 ft incremental for Well 12071 is about -0.1932, which shows a poor relationship. Artificial Neutral Network (ANN) was used to establish the relationship which can be used to predict the actual petrophysical properties of the formation in other wells.

The EOR screening method from Taber et al. (1997) is to a good extent applicable to the Dawson Bay Formation, Dolphin Field. Surfactant flooding and CO_2-EOR methods are applicable to the formation based on experimental results and CO_2 numerical simulation.

The brine, surfactant and CO_2 flooding will improve oil recovery from the formation though in varying degrees. The surfactant and brine stimulation gave the highest yield of all from experimental results. The prevailing economics, cost of surface and injection plants, environmental among other considerations will eventually determine which method to use at a time of EOR operation.

5.2 Recommendations

The pilot test is recommended for surfactant imbibition and CO_2 'HnP' Enhanced Oil Recovery methods on Dawson Bay Formation of Dolphin Field, in North Dakota. The detailed design of the best surface and injection facilities for EOR with discounted economics is necessary for successful EOR operation.

Further study on applicability of some other EOR methods which may be applicable to the formation and the field e.g. hydrocarbon gas is recommended.

APPENDICES

Appendix I. Converted Digital Well Logs and Results of Petra Calculations

Converted Digital Well Logs and Results of Petra Calculation

```
~Version Information
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 WRAP.                 YES:
 END.                PETRA:GeoPLUS Corporation
~Well Information Block
#MNEM.UNIT       Data Type    Information
#---------    -------------   --------------------------------
 STRT.F          9974.0000:
 STOP.F         10118.0000:
 STEP.F             0.5000:
 NULL.             -999.25:
 COMP.                        : COMPANY
 FLD.                         : FIELD
 LOC.                         : LOCATION
 DATE.      19-JAN-2018       : DATE
 WELL.                        : Well Name
 LABL.      33-023-00369-00-00            : Well Label
 APIN.      33-023-00369-00-00   : API Number
 UWI.       33-023-00369-00-00   : Unique Well Number
 NUMB.      12085             : Well Number
~Parameter Block
#MNEM.UNIT           VALUE           Description
#---------    --------------------   --------------------------------
~Curve Information Block
#MNEM.UNIT      API CODE      Curve Description
#---------    -------------   --------------------------------
 DEPT.F                  00 000 00 00: Depth (MD)
 DEPT.FT                 00 001 00 00: Depth in Feet
 DPHI.%                  00 002 00 00: Density Porosity
 GR.GAPI                 00 003 00 00: Gamma Ray
 LLD.OHMM                00 004 00 00: Latero-Log Deep (Resistivity)
 NPHI.%                  00 005 00 00: Neutron Porosity
 PHIA.%                  00 006 00 00: AVG POR
 SHC.                    00 007 00 00: HYDROCARBON SATURATION
 SW.V/V                  00 008 00 00: WATER SAT.
~A

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  -2.582      0.999     0.001
 9975.000
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 STRT.F           9930.0000:
 STOP.F          10116.0000:
 STEP.F              0.5000:
 NULL.              -999.25:
 COMP.                           : COMPANY
 FLD.                            : FIELD
 LOC.                            : LOCATION
 DATE.      19-JAN-2018          : DATE
 WELL.                           : Well Name
 LABL.      33-023-00379-00-00               : Well Label
 APIN.      33-023-00379-00-00   : API Number
 UWI.       33-023-00379-00-00   : Unique Well Number
 NUMB.      12245                : Well Number
~Parameter Block
#MNEM.UNIT           VALUE            Description
#---------    --------------------   --------------------------------
~Curve Information Block
#MNEM.UNIT      API CODE      Curve Description
#---------    -------------   --------------------------------
 DEPT.F                  00 000 00 00: Depth (MD)
 DEPT.FT                 00 001 00 00: Depth in Feet
 DPHI.%                  00 002 00 00: Density Porosity
 GR.GAPI                 00 003 00 00: Gamma Ray
 LLD.OHMM                00 004 00 00: Latero-Log Deep (Resistivity)
 NPHI.%                  00 005 00 00: Neutron Porosity
 PHIA.%                  00 006 00 00: AVG POR
 SHC.                    00 007 00 00: HYDROCARBON SATURATION
 SW.V/V                  00 008 00 00: WATER SAT.
~A
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 9930.000   -999.25   -999.25   288.735   -999.25
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 9930.500   -999.25   -999.25   288.735   -999.25
  -999.25   -999.25   -999.25
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  -999.25   -999.25   -999.25
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 FLD.                             : FIELD
 LOC.                             : LOCATION
 DATE.      19-JAN-2018           : DATE
 WELL.                            : Well Name
 LABL.      33-023-00364-00-00                : Well Label
 APIN.      33-023-00364-00-00    : API Number
 UWI.       33-023-00364-00-00    : Unique Well Number
 NUMB.      12017                 : Well Number
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 DPHI.%                  00 002 00 00: Density Porosity
 GR.GAPI                 00 003 00 00: Gamma Ray
 LLD.OHMM                00 004 00 00: Latero-Log Deep (Resistivity)
 NPHI.%                  00 005 00 00: Neutron Porosity
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 FLD.                               : FIELD
 LOC.                               : LOCATION
 DATE.      19-JAN-2018             : DATE
 WELL.                              : Well Name
 LABL.      33-023-00368-00-00                  : Well Label
 APIN.      33-023-00368-00-00      : API Number
 UWI.       33-023-00368-00-00      : Unique Well Number
 NUMB.      12079                   : Well Number
~Parameter Block
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~Curve Information Block
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 DEPT.FT                  00 001 00 00: Depth in Feet
 DPHI.%                   00 002 00 00: Density Porosity
 GR.GAPI                  00 003 00 00: Gamma Ray
 LLD.OHMM                 00 004 00 00: Latero-Log Deep (Resistivity)
 NPHI.%                   00 005 00 00: Neutron Porosity
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 APIN.      33-023-00367-00-00     : API Number
 UWI.       33-023-00367-00-00     : Unique Well Number
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9918.000 -9.814 13.178 1882.162 2.167

-3.823 0.999 0.001

9918.500

9918.500 -9.873 13.726 1818.928 1.787

-4.043 0.999 0.001

9919.000

9919.000 -9.934 14.563 1835.577 1.542

-4.196 0.999 0.001

9919.500

9919.500 -9.995 15.155 1940.169 1.426

-4.285 0.999 0.001

9920.000

9920.000 -10.036 15.013 2003.109 1.310

-4.363 0.999 0.001

9920.500

9920.500 -10.054 13.335 1973.709 1.130

-4.462 0.999 0.001

9921.000

9921.000 -10.072 8.286 1980.122 0.835

-4.619 0.999 0.001

9921.500

9921.500 -10.064 8.125 2012.476 0.974

-4.545 0.999 0.001

9922.000

9922.000 -10.036 8.201 2000.813 1.113

-4.461 0.999 0.001

9922.500

9922.500 -10.027 8.347 1825.342 1.479

-4.274 0.999 0.001

9923.000

9923.000 -9.920 9.208 1845.819 1.952

-3.984 0.999 0.001

9923.500

9923.500 -8.003 11.931 1888.597 2.684

-2.659 0.999 0.001

9924.000

9924.000 -5.006 13.190 1917.018 3.727

-0.639 0.995 0.005

9924.500

9924.500 -3.758 13.521 1988.621 5.313

0.778 0.996 0.004

9925.000

9925.000 -3.103 13.058 2000.983 6.400

1.649 0.998 0.002

9925.500

9925.500 -1.931 12.592 2005.662 11.065

4.567 0.999 0.001

9926.000

9926.000 -1.042 12.457 2002.075 12.287

5.622 0.999 0.001

9926.500

9926.500 -0.564 12.442 2004.520 13.184

6.310 0.999 0.001

9927.000

9927.000 -0.120 12.397 2003.072 14.154

7.017 1.000 0.000

9927.500

9927.500 -0.386 11.303 2003.851 13.245

6.429 1.000 0.000

9928.000

9928.000 -1.025 9.577 2003.888 11.971

5.473 0.999 0.001

9928.500

9928.500 -1.025 9.260 2003.346 10.651

4.813 0.999 0.001

9929.000

9929.000 0.698 9.405 1994.708 10.454

5.576 0.999 0.001

9929.500

9929.500 1.585 11.880 1985.357 10.909

6.247 0.999 0.001

9930.000

9930.000 2.064 13.295 1930.905 11.548

6.806 1.000 0.000

9930.500

9930.500 1.850 13.033 1841.439 12.316

7.083 1.000 0.000

9931.000

9931.000 1.151 13.439 1781.607 13.835

7.493 1.000 0.000

9931.500

9931.500 0.841 12.479 1705.736 13.084

6.963 1.000 0.000

9932.000

9932.000 0.730 10.727 1639.180 13.062

6.896 0.999 0.001

9932.500

9932.500 0.620 10.150 1608.533 13.040

6.830 0.999 0.001

9933.000

9933.000 0.151 9.544 1552.766 13.036

6.594 0.999 0.001

9933.500

9933.500 0.060 9.130 1556.440 13.039

6.550 0.999 0.001

9934.000

9934.000 -0.013 8.704 1571.891 12.829

6.408 0.999 0.001

9934.500

9934.500 -0.149 8.291 1578.980 12.520

6.185 0.999 0.001

9935.000

9935.000 -0.572 7.876 1606.276 12.221

5.825	0.999	0.001		
9935.500				
9935.500	-1.132	6.983	1638.256	11.720
5.294	0.999	0.001		
9936.000				
9936.000	-0.852	6.251	1709.749	10.969
5.058	0.999	0.001		
9936.500				
9936.500	-0.429	6.216	1811.075	10.731
5.151	0.999	0.001		
9937.000				
9937.000	-0.078	6.152	1926.763	10.465
5.194	0.999	0.001		
9937.500				
9937.500	0.206	6.077	1998.290	10.310
5.258	0.999	0.001		
9938.000				
9938.000	0.306	6.068	1999.768	10.287
5.297	0.999	0.001		
9938.500				
9938.500	-0.012	6.828	1998.690	10.266
5.127	0.999	0.001		
9939.000				
9939.000	-0.388	5.062	2000.872	10.218
4.915	0.999	0.001		
9939.500				
9939.500	-1.036	6.157	1999.671	10.172
4.568	0.999	0.001		
9940.000				

9940.000 -1.483 6.524 2001.452 10.126

4.322 0.999 0.001

9940.500

9940.500 -1.611 6.481 2001.031 11.225

4.807 0.999 0.001

9941.000

9941.000 -0.893 6.316 2001.928 12.046

5.577 0.999 0.001

9941.500

9941.500 -0.153 6.305 2002.342 12.840

6.343 1.000 0.000

9942.000

9942.000 0.573 6.299 2002.665 12.960

6.766 1.000 0.000

9942.500

9942.500 3.910 6.285 2003.400 13.028

8.469 1.000 0.000

9943.000

9943.000 7.124 6.757 2003.675 13.509

10.316 1.000 0.000

9943.500

9943.500 6.591 7.397 2003.121 15.273

10.932 1.000 0.000

9944.000

9944.000 8.774 7.893 2002.115 16.332

12.553 1.000 0.000

9944.500

9944.500 9.071 8.138 2001.361 18.186

13.629 1.000 0.000

9945.000

9945.000 7.536 7.971 2000.509 19.960

13.748 1.000 0.000

9945.500

9945.500 5.604 7.816 1999.551 19.587

12.595 1.000 0.000

9946.000

9946.000 4.574 7.666 1998.983 19.907

12.240 1.000 0.000

9946.500

9946.500 4.408 7.347 1997.638 19.381

11.894 1.000 0.000

9947.000

9947.000 4.345 6.990 1997.421 19.072

11.709 1.000 0.000

9947.500

9947.500 4.295 6.588 1995.746 18.630

11.462 1.000 0.000

9948.000

9948.000 4.248 6.162 1996.687 18.241

11.244 1.000 0.000

9948.500

9948.500 4.248 6.341 1996.582 17.834

11.041 1.000 0.000

9949.000

9949.000 4.252 6.788 1999.204 17.403

10.828 1.000 0.000

9949.500

9949.500 3.950 7.246 1999.222 16.338

10.144 1.000 0.000

9950.000

9950.000 3.503 7.677 1997.857 15.830

9.667 1.000 0.000

9950.500

9950.500 3.042 8.328 2005.551 15.372

9.207 1.000 0.000

9951.000

9951.000 1.967 8.754 1993.678 14.659

8.313 1.000 0.000

9951.500

9951.500 1.096 8.569 1947.745 13.632

7.364 1.000 0.000

9952.000

9952.000 1.285 8.482 1881.683 12.397

6.841 1.000 0.000

9952.500

9952.500 1.567 8.034 1831.049 12.806

7.187 1.000 0.000

9953.000

9953.000 1.966 7.796 1845.727 13.440

7.703 1.000 0.000

9953.500

9953.500 2.364 8.340 1887.425 14.687

8.525 1.000 0.000

9954.000

9954.000 2.499 7.837 1904.494 15.998

9.249 1.000 0.000

9954.500

9954.500 2.613 7.609 1917.335 16.380

9.496 1.000 0.000

9955.000

9955.000 2.066 7.547 1929.319 16.323

9.194 1.000 0.000

9955.500

9955.500 1.265 7.493 1937.826 15.406

8.335 1.000 0.000

9956.000

9956.000 0.582 7.441 1950.670 13.989

7.285 1.000 0.000

9956.500

9956.500 0.011 7.404 1959.963 12.251

6.131 0.999 0.001

9957.000

9957.000 -0.593 6.966 1971.115 11.438

5.423 0.999 0.001

9957.500

9957.500 -1.093 6.485 1980.840 10.536

4.722 0.999 0.001

9958.000

9958.000 -1.296 5.442 1991.390 10.741

4.722 0.999 0.001

9958.500

9958.500 -1.480 5.431 1998.793 10.937

4.728 0.999 0.001

9959.000

9959.000 -2.320 5.646 1996.404 10.771

4.225 0.999 0.001

9959.500

9959.500 -2.730 5.867 1982.636 10.480

3.875 0.999 0.001

9960.000

9960.000 -2.253 6.077 1940.637 10.156

3.952 0.999 0.001

9960.500

9960.500 -1.611 6.209 1891.812 9.895

4.142 0.999 0.001

9961.000

9961.000 -0.549 6.345 1878.411 10.219

4.835 0.999 0.001

9961.500

9961.500 -0.280 6.490 1863.885 10.575

5.148 0.999 0.001

9962.000

9962.000 -0.440 6.818 1836.502 10.871

5.215 0.999 0.001

9962.500

9962.500 -0.595 7.484 1827.242 10.959

5.182 0.999 0.001

9963.000

9963.000 -1.558 7.875 1813.882 10.388

4.415 0.999 0.001

9963.500

9963.500 -1.608 7.705 1820.316 9.707

4.049 0.999 0.001

9964.000

9964.000 -1.654 7.555 1810.772 9.010

3.678 0.999 0.001

9964.500

9964.500 -1.700 7.432 1739.857 8.384

3.342 0.999 0.001

9965.000

9965.000 -2.146 6.772 1710.745 7.791

2.822 0.999 0.001

9965.500

9965.500 -2.637 6.035 1663.640 7.260

2.312 0.999 0.001

9966.000

9966.000 -2.889 5.257 1633.991 6.911

2.011 0.998 0.002

9966.500

9966.500 -1.660 5.147 1729.052 7.330

2.835 0.999 0.001

9967.000

9967.000 -0.643 5.492 1852.224 8.224

3.791 0.999 0.001

9967.500

9967.500 0.040 5.843 1929.679 9.764

4.902 0.999 0.001

9968.000

9968.000 0.093 6.189 1892.993 10.091

5.092 0.999 0.001

9968.500

9968.500 -0.615 6.620 1888.175 10.363

4.874 0.999 0.001

9969.000

9969.000 -1.582 7.105 1923.081 10.407

4.412 0.999 0.001

9969.500

9969.500 -2.354 7.621 1863.547 10.310

3.978 0.999 0.001

9970.000

9970.000 -2.284 8.187 1802.552 9.754

3.735 0.999 0.001

9970.500

9970.500 -1.886 13.128 1789.845 9.651

3.882 0.999 0.001

9971.000

9971.000 -1.361 14.488 1776.995 9.831

4.235 0.999 0.001

9971.500

9971.500 -0.744 14.111 1761.935 10.116

4.686 0.999 0.001

9972.000

9972.000 -0.067 11.327 1750.747 11.369

5.651 0.999 0.001

9972.500

9972.500 1.593 9.486 1735.758 12.610

7.101 1.000 0.000

9973.000

9973.000 1.942 11.130 1776.411 13.121

7.531 1.000 0.000

9973.500

9973.500 2.061 9.442 1776.360 13.609

7.835 1.000 0.000

9974.000

9974.000 1.603 8.392 1776.360 14.121

7.862 1.000 0.000

9974.500

9974.500 1.259 9.458 1776.360 14.208

7.733 1.000 0.000

9975.000

9975.000 0.787 10.800 1776.360 14.084

7.435 1.000 0.000

9975.500

9975.500 0.212 10.695 1776.360 13.909

7.060 1.000 0.000

9976.000

9976.000 -3.827 9.171 1776.360 6.751

1.462 0.998 0.002

9976.500

9976.500 -3.827 9.171 1776.360 6.751

1.462 0.998 0.002

9977.000

9977.000 -3.827 9.171 1776.360 6.751

1.462 0.998 0.002

9977.500

9977.500 -3.827 9.171 1776.360 6.751

1.462 0.998 0.002

9978.000

9978.000 -3.827 9.171 1776.360 6.751

1.462 0.998 0.002

9978.500

9978.500 -999.25 -999.25 1776.360 -999.25

-999.25 -999.25 -999.25

9979.000

9979.000 -999.25 -999.25 1776.360 -999.25

-999.25 -999.25 -999.25

9979.500

9979.500 -999.25 -999.25 1776.360 -999.25

-999.25 -999.25 -999.25

9980.000

9980.000 -999.25 -999.25 1776.360 -999.25

-999.25 -999.25 -999.25

Appendix II. Experimental Procedures.

Measurement of effective porosity of cores using weight method.

The preparation of the core samples:

1. The cores were cleaned with with toluene and methanol and they were dried in the oven at 105°C for 24 hours.
2. The cores were vacuumed for 2 hours to remove any gas from the lines and core.
3. The cores' length (thickness) and diameter were measured at 5 locations using a Vernier caliper. The measurements were recorded.
4. The cleaned and dried core samples were weighed with analytic balance. The weight values were recorded.

Saturation of the core using an ISCO pump to achieve 100% saturation. The core plugs were installed in Hassler Cell. The following procedures were employed:

(1) The test liquid (filtered oil) was pumped into the core sample (a transfer cylinder was used to avoid the pump corrosion).

(2) The oil was injected until a relative constant pressure was reached.

(3) After the first liquid drop was produced, the pressure changes were observed and recorded. Pressure stability was observed for days.

(4) The pump was stopped; the core sample was taken out from the hassler cell and the mass was weighed immediately.

Effective porosity of the cores was determined by weight differences before and after saturation with the oil of measured density. Weight measurements were made using an analytical balance that read weights to 0.0001 g. Eq. 1 provide the method for porosity determination:

$\phi = (W_o - W_{dry})/(\rho_o V)$, ... eqn. 1

Where,

ϕ ---- effective porosity, dimensionless;

W_{dry} ---- dry weight of the rock, *g*;

W_o and W_w ---- weights of core samples after oil saturations;

ρ_o, ---- oil density, g/cm^3;

V ---- bulk volume of the rock, cm^3.

Spreadsheet:

Porosity						EFFECTIVE POROSITY				
S/No	core no	dry mass (g)	saturated mass (g)	saturated mass-dry mass (g)	oil density (g/cm3)	core length (cm)	core diameter (cm)	core base area (cm2)	bulk volume of rock= 3.142*((H4)^2)/4)*G4	porosity
1	71-2	107.0083	108.6828	1.6745	0.912	5.042	3.1858		40.19629701	0.024877913
2	71-3	108.778	110.0751	1.2971	0.912	5.0758	3.2008		40.84771502	0.024481174
3	85-1	117.2381	120.3484	3.1103	0.912	5.7306	3.186		45.69175377	0.021885787
4	85-4	106.2921	106.6387	0.3466	0.912	5.1008	3.175		40.38982245	0.024758712
5	85-5	103.499	103.8135	0.3145	0.912				0	#DIV/0!
6	114-1	107.7825	108.1123	0.3298	0.912	5.0828	3.1768		40.29294015	0.024818244
7	114-2	103.884	105.8062	1.9222	0.912	4.99	3.175		39.51247138	0.025308465
8	149-2	108.2534	109.2443	0.9909	0.912	5.011	3.192		40.10480024	0.024934671
9	149-3	103.256	104.8968	1.6408	0.912	5.0902	3.1966		40.85616758	0.024476109

Nuclear Magnetic Resonance for Porosity Distributions

The samples were cleaned with toluene and methanol (1:1 by volume) in a dean stark. After the cores were dried in an oven. They were evacuated of air using vacuum pump. The cores were saturated in the brine of concentration of the formation. They were saturated for about 60 days.

Since NMR porosity is based on fluid filled pores, the samples must be fully saturated with the brine solution. After the samples had been fully saturated, pore-size distributions were obtained using NMR T2 analysis in Oxford Instruments Geospec 2 core analyzer which is coupled with Green Imaging Technologies software 7.5.0. The machine was calibrated with a resonance frequency of 2.455 MHz and τ was set at 56 µs; this was the shortest τ allowed by the equipment that still allowed the use of a short (125 kHz) bandpass filter to improve the signal-to-noise ratio (SNR). Dunn et al., (2002) says that the short τ makes signal to be received from small pores with very short T2 and it also diminishes dephasing effects (Dunn et al. 2002). The wait time between CPMG pulse sequences was set to 750 ms. The Hydrogen index is the amount of hydrogen per unit volume of a fluid divided by the amount of hydrogen per unit volume of a pure water (Dunn et al. 2002). Each sample was ran until a SNR of at least 100 was achieved. Pore-size distributions were inferred from NMR T2 curves based on the curves' performances.
The porosities for each core were partitioned into three pore-size classes. Clay bound, capillary and free fluid porosities.

Measurement of Effective Permeability using ISCO Pump

The equipment are ISCO Pump and Hassler core holder
The materials are Core plugs, crude oil from Dawson Bay Formation.

Procedure: Core sample preparation**:**
1**.** The core samples were cleaned with toluene and methanol in dean stark, and they were dried in the oven at the temperature of 105°C for 24 hours.
2. The core samples were vacuumed for 2 hours to remove any gas from the lines and core.
3. Measurements of core samples' length (thickness) and diameter, and weighing of the mass of the core samples.

Fluid preparation (crude oil)
1. Filtering of the oil through Whatman 4™ filter paper;
2. Measurement of the viscosity of the crude oil using a Brookfield viscometer with UL-Adapter.

Based on Darcy's law, $k = q\mu L/(A\Delta P)$

K= permeability, d

Q= flow rate, ml/sec., reading from ISCO pump (note: 1 ml/Hr = 1 ml/3600 s)

μ = fluid viscosity, cP

L = length of core sample, cm

A =cross-section area, π*(D/2)^2, D is the diameter of the core sample, cm^2

ΔP= pressure gradient, atm.

Measurement of the absolute permeability k_o

1. Placing of the core plug into the core holder Hassler Cell.
2. Pumping distilled water into the ISCO pump B and apply confining pressure at 500 psi.
3. Pumping of the oil into ISCO pump A (injection pump)
4. Running of the injection pump A at a constant flow rate until the oil comes out and a constant pressure is reached
5. The pressure drop change (the difference between pressure gauge and the out pressure) was recorded, flow rate reading from ISCO pump.
6. The **absolute permeability k_o** was determined by Darcy's Law

Absolute permeability K_o

Core sample #: ___________________.

q, ml/sec., flow rate, reading from ISCO pump ________**ml/hr.** (should convert to **ml/Sec**.)

Convert to ________________**ml/Sec**.

μ, oil viscosity _____________cp (0.9775 at 21° C, 0.9544 at 22°C)

L, cm. length of core sample _________cm

ΔP, atm. pressure gradient _____________psi (should convert to atm. 1psi =0.068 atm.)

Convert to ________________**atm**.

A, cm^2, cross-section area (Diameter of core sample: ________cm): _______________ cm^2

K_w, permeability ___________ d ____________md

S/No	core no	Oil vol. 1 (mL)	Flow Rate (ml/s)	Flow Rate (Average) mL/Hr	oil viscosity (cp)	core length (cm)	core diameter (cm)	core base area (cm2)	AP (atm)	k(d)		AP (psi)
1	71-2		0.000141667	0.51	4.1	5.042	3.1858	7.972292148	9.112	4.03141E-05		134
2	71-3		0.000140278	0.505	4.1	5.0758	3.2008	8.047542263	2.244	0.000161656		33
3	85-1		0.000140278	0.505	4.1	5.7306	3.186	7.973293158	1.7	0.000243157		25
4	85-4		0.000555556	2	4.1	5.1008	3.175	7.918330938	1.564	0.000938165		23
5	85-5		0		4.1			0	0	#DIV/0!		
6	114-1		0.000279167	1.005	4.1	5.0828	3.1768	7.927311748	12.24	5.99574E-05		180
7	114-2		0.000338611	1.219	4.1	4.99	3.175	7.918330938	6.12	0.000142955		90
8	149-2		0.000625	2.25	4.1	5.011	3.192	8.003352672	6.12	0.000262159		90
9	149-3		0.000805556	2.9	4.1	5.0902	3.1966	8.0264366	6.12	0.000342247		90

Core	Effective Por.	Effective Perm.
71-2	0.024877913	4.03E-05
71-3	0.024481174	0.000161656
85-1	0.021885787	0.000243157
85-4	0.024758712	0.000938165
114-1	0.024818244	6.00E-05
114-2	0.025308465	0.000142955
149-2	0.024934671	0.000262159
149-3	0.024476109	0.000342247

Measurement of Fluid Viscosity Using Brookfield Digital Viscometer

Procedure

1. Inserting and centering of the spindle in the test material (oil, 600 ml) until the level of the is at the immersion groove on the spindle's shaft. it is sometimes necessary to title the spindle slightly while immersing to avoid trapping air bubbles on its underside surface with a disc-type spindle.

2. Mounting of the guardleg on the DV-E viscometer (LV or RV) series). Ensuring that the motor is OFF before attaching the spindle. Selection of a spindle and attaching it to the spindle coupling nut. Lifting of the shaft slightly, holding it firmly with one hand while screwing the spindle on with other (left-hand thread should be noted). One should avoid putting side thrust on the shaft.

3. In order to make a viscosity measurement, selection of a speed (Spindle LV1 is 61, UL adapter is 00). Allowing time for the indicated reading to stabilize. The time required for stabilization will depend on the speed at which the Viscometer is running and the characteristics of the sample fluid. To achieve the maximum accuracy, flashing readings below 10% should be avoided.

4. Switching of the MOTOR ON/OFF switch to turn the motor 'OFF" when changing a spindle or changing sample. Removal of the spindle before cleaning.

5. Interpreting the results.

Appendix III. The Spread Sheet of Surfactant Imbibition Results.

Core 71-2					
IBM cell		104.44 C	Base brine (4% salinity) + VX12279 @ 0.2%		Depth: 9924.5 ft
				oil recovery	
		Time,Hr	oil,ml		tD
13-Mar	12:25:00 pM	0	0	0	0
	1:10:00 pM	0	0.2	6.448830523	0
	1:40:00 pM	0.5	**0.3**	9.673245784	1.844644234
	14:10	1	**0.4**	12.89766105	3.689288468
	3:10:00 PM	2	0.4	12.89766105	7.378576936
	5:10:00 PM	4	0.4	12.89766105	14.75715387
	9.10 pm	8	0.45	14.50986868	29.51430774
14-Mar	1.10 am	12	0.45	14.50986868	44.27146161
	1.10 pm	24	0.55	17.73428394	88.54292323
15-Mar	1.10 pm	48	0.7	22.57090683	177.0858465
16-Mar	1.10 pm	72	0.8	25.79532209	265.6287697
17-Mar	1.12 pm	96	0.8	25.79532209	354.1716929
18-Mar	1.06 pm	120	0.8	25.79532209	442.7146161
19-Mar	1.10 pm	144	0.8	25.79532209	531.2575394
20-Mar	1.12 pm	168	0.8	25.79532209	619.8004626
21-Mar	1.30 pm	192.3	0.9	29.01973735	709.4501724
22-Mar	1.18 pm	216	0.9	29.01973735	796.8863091
23-Mar	**2.45 pm**	240.5	0.95	30.63194498	887.2738765
24-Mar	**4.15 pm**	264	0.95	30.63194498	973.9721555
25-Mar	**1.50 pm**	288.5	0.98	31.59926956	1064.359723
26-Mar	**1.10 pm**	312	0.98	31.59926956	1151.058002
27-Mar	**1.10 pm**	336	1	32.24415261	1239.600925
28-Mar	**1.10 pm**	360	1	32.24415261	1328.143848
29-Mar	**1.07 pm**	384	1	32.24415261	1416.686772
30-Mar	**9.30 am**	403.22	1	32.24415261	1487.594896
31-Mar	**1.13 pm**	432	1	32.24415261	1593.772618
1-Apr	**1.05 pm**	456	1.05	33.85636025	1682.315541
2-Apr	1.25 pm	480.33	1.05	33.85636025	1772.07593
3-Apr	1.10 pm	504	1.07	34.5012433	1859.401388
4-Apr	1.10 pm	528	1.1	35.46856788	1947.944311
5-Apr	1.30 pm	552.3	1.1	35.46856788	2037.594021
6-Apr	1.15 pm	586	1.15	37.08077551	2161.923042
7-Apr	1.15 pm	610	1.17	37.72565856	2250.465965
8-Apr	1.35 pm	634.5	1.2	38.69298314	2340.853533
9-Apr	2.34 pm	658.5	1.25	40.30519077	2429.396456
10-Apr	2.18 pm	682.5	1.25	40.30519077	2517.939379
11-Apr	1.30 pm	706.5	1.25	40.30519077	2606.482303
12-Apr	12.45 pm	730.5	1.28	41.27251535	2695.025226
13-Apr	1.45 pm	754.5	1.28	41.27251535	2783.568149
14-Apr	1.50 pm	778.5	1.3	41.9173984	2872.111072
15-Apr	1.25 pm	802	1.35	43.52960603	2958.809351
16-Apr	1.10 pm	825.7	1.35	43.52960603	3046.245488
17-Apr	1.10 pm	849.7	1.35	43.52960603	3134.788411
18-Apr	1.25 pm	874	1.35	43.52960603	3224.438121
19-Apr	1.10 pm	897.7	1.35	43.52960603	3311.874258
20-Apr	1.30 pm	922	1.35	43.52960603	3401.523967
21-Apr	1.30 pm	946	1.35	43.52960603	3490.066891
22-Apr	1.40 pm	970	1.35	43.52960603	3578.609814
23-Apr	1.20 pm	993.7	1.36	43.85204756	3666.04595
24-Apr	11.33 am	1017.7	1.38	44.49693061	3754.588874

				Depth (ft.)		
				9924.5		
	Core					
	D=	31.858				
	L=	50.42				
	Dry=	106.9915				
	Oil saturation	109.5653				
		weight, g	Oil weight in core	Oil volume in core	Oil volume in core	
	dry	106.9915				
	Oil saturation	109.5653	2.5738	3.112212817	3.890266022	
				3.209713219		
				3.292225127		
				3.383555018		
				3.461285336		

IBM cell		104.1 C	Base brine @ 10%	Depth: 9930 ft.	
Core 71-3				oil recovery	
		Time,Hr	oil,ml		tD
13-Mar	12:25:00 pM	0	0	0	0
	1:10:00 pM	0	0	0	0
	1:40:00 pM	0.5	0	0	1.844644234
	14:10	1	0	0	3.689288468
	3:10:00 PM	2	0	0	7.378576936
	5:10:00 PM	4	0	0	14.75715387
	9.10 pm	8	0	0	29.51430774
14-Mar	1.10 am	12	0	0	44.27146161
	1.10 pm	24	0.001	0.136026881	88.54292323
15-Mar	1.10 pm	48	0.02	2.720537617	177.0858465
16-Mar	1.10 pm	72	0.2	27.20537617	265.6287697
17-Mar	1.12 pm	96	0.2	27.20537617	354.1716929
18-Mar	1.06 pm	120	0.25	34.00672021	442.7146161
19-Mar	1.10 pm	144	0.25	34.00672021	531.2575394
20-Mar	1.12 pm	168	0.3	40.80806425	619.8004626
21-Mar	1.30 pm	192.3	0.3	40.80806425	709.4501724
22-Mar	1.18 pm	216	0.3	40.80806425	796.8863091
23-Mar	**2.45 pm**	240.5	0.3	40.80806425	887.2738765
24-Mar	**4.15 pm**	264	0.35	47.60940829	973.9721555
25-Mar	**1.50 pm**	288.5	0.35	47.60940829	1064.359723
26-Mar	**1.10 pm**	312	0.35	47.60940829	1151.058002
27-Mar	**1.10 pm**	336	0.35	47.60940829	1239.600925
28-Mar	**1.10 pm**	360	0.35	47.60940829	1328.143848
29-Mar	**1.07 pm**	384	0.35	47.60940829	1416.686772
30-Mar	**9.30 am**	403.22	0.35	47.60940829	1487.594896
31-Mar	**1.13 pm**	432	0.35	47.60940829	1593.772618
1-Apr	**1.05 pm**	456	0.35	47.60940829	1682.315541
2-Apr	1.25 pm	480.33	0.35	47.60940829	1772.07593
3-Apr	1.10 pm	504	0.35	47.60940829	1859.401388
4-Apr	1.10 pm	528	0.4	54.41075234	1947.944311
5-Apr	1.30 pm	552.3	0.4	54.41075234	2037.594021
6-Apr	1.15 pm	586	0.4	54.41075234	2161.923042
7-Apr	1.15 pm	610	0.4	54.41075234	2250.465965
8-Apr	1.35 pm	634.5	0.4	54.41075234	2340.853533
9-Apr	2.34 pm	658.5	0.4	54.41075234	2429.396456
10-Apr	2.18 pm	682.5	0.4	54.41075234	2517.939379
11-Apr	1.30 pm	706.5	0.4	54.41075234	2606.482303
12-Apr	12.45 pm	730.5	0.4	54.41075234	2695.025226
13-Apr	1.45 pm	754.5	0.4	54.41075234	2783.568149
14-Apr	1.50 pm	778.5	0.4	54.41075234	2872.111072
15-Apr	1.25 pm	802	0.4	54.41075234	2958.809351
16-Apr	1.10 pm	825.7	0.4	54.41075234	3046.245488
17-Apr	1.10 pm	849.7	0.4	54.41075234	3134.788411
18-Apr	1.25 pm	874	0.4	54.41075234	3224.438121
19-Apr	1.10 pm	897.7	0.4	54.41075234	3311.874258
20-Apr	1.30 pm	922	0.4	54.41075234	3401.523967
21-Apr	1.30 pm	946	0.4	54.41075234	3490.066891
22-Apr	1.40 pm	970	0.4	54.41075234	3578.609814
23-Apr	1.20 pm	993.7	0.4	54.41075234	3666.04595
24-Apr	11.33 am	1017.7	0.4	54.41075234	3754.588874

	IBM cell		104.1 C			Base brine (10% salinity) +VX12279 @ 0.1%
	Core 85-4				oil recovery	
			Time,Hr	oil,ml		tD
	13-Mar	12:25:00 pM	0		0	0
		1:10:00 pM	0	0.01	1.558497653	0
0		1:40:00 pM	0.5	0.04	6.23399061	1.844644234
0.5		14:10	1	0.05	7.792488263	3.689288468
		3:10:00 PM	2	0.05	7.792488263	7.378576936
1		5:10:00 PM	4	0.2	31.16995305	14.75715387
2		9.10 pm	8	0.2	31.16995305	29.51430774
3	14-Mar	1.10 am	12	0.28	43.63793427	44.27146161
4		1.10 pm	24	0.28	43.63793427	88.54292323
6	15-Mar	1.10 pm	48	0.28	43.63793427	177.0858465
8	16-Mar	1.10 pm	72	0.3	46.75492958	265.6287697
19	17-Mar	1.12 pm	96	0.31	48.31342723	354.1716929
24	18-Mar	1.06 pm	120	0.31	48.31342723	442.7146161
	19-Mar	1.10 pm	144	0.31	48.31342723	531.2575394
	20-Mar	1.12 pm	168	0.31	48.31342723	619.8004626
	21-Mar	1.30 pm	192.3	0.31	48.31342723	709.4501724
	22-Mar	1.18 pm	216	0.31	48.31342723	796.8863091
	23-Mar	**2.45 pm**	240.5	0.31	48.31342723	887.2738765
	24-Mar	**4.15 pm**	264	0.31	48.31342723	973.9721555
	25-Mar	**1.50 pm**	288.5	0.31	48.31342723	1064.359723
	26-Mar	**1.10 pm**	312	0.31	48.31342723	1151.058002
	27-Mar	**1.10 pm**	336	0.31	48.31342723	1239.600925
	28-Mar	**1.10 pm**	360	0.31	48.31342723	1328.143848
	29-Mar	**1.07 pm**	384	0.31	48.31342723	1416.686772
	30-Mar	**9.30 am**	403.22	0.31	48.31342723	1487.594896
	31-Mar	**1.13 pm**	432	0.31	48.31342723	1593.772618
	1-Apr	**1.05 pm**	456	0.31	48.31342723	1682.315541
	2-Apr	1.25 pm	480.33	0.31	48.31342723	1772.07593
	3-Apr	1.10 pm	504	0.31	48.31342723	1859.401388
	4-Apr	1.10 pm	528	0.31	48.31342723	1947.944311
	5-Apr	1.30 pm	552.3	0.31	48.31342723	2037.594021
	6-Apr	1.15 pm	586	0.31	48.31342723	2161.923042
	7-Apr	1.15 pm	610	0.31	48.31342723	2250.465965
	8-Apr	1.35 pm	634.5	0.31	48.31342723	2340.853533
	9-Apr	2.34 pm	658.5	0.31	48.31342723	2429.396456
	10-Apr	2.18 pm	682.5	0.31	48.31342723	2517.939379
	11-Apr	1.30 pm	706.5	0.31	48.31342723	2606.482303
	12-Apr	12.45 pm	730.5	0.31	48.31342723	2695.025226
	13-Apr	1.45 pm	754.5	0.31	48.31342723	2783.568149
	14-Apr	1.50 pm	778.5	0.31	48.31342723	2872.111072
	15-Apr	1.25 pm	802	0.31	48.31342723	2958.809351
	16-Apr	1.10 pm	825.7	0.31	48.31342723	3046.245488
	17-Apr	1.10 pm	849.7	0.31	48.31342723	3134.788411
	18-Apr	1.25 pm	874	0.31	48.31342723	3224.438121
	19-Apr	1.10 pm	897.7	0.31	48.31342723	3311.874258
	20-Apr	1.30 pm	922	0.31	48.31342723	3401.523967
	21-Apr	1.30 pm	946	0.31	48.31342723	3490.066891
	22-Apr	1.40 pm	970	0.31	48.31342723	3578.609814
	23-Apr	1.20 pm	993.7	0.31	48.31342723	3666.04595
	24-Apr	11.33 am	1017.7	0.31	48.31342723	3754.588874

	IBM cell		104.1 C			Base brine (15% salinity+VX12279@0.1%)
	Core 114-1				oil recovery	
			Time,Hr	oil,ml	Base brine	tD
	13-Mar	12:25:00 pM	0	0	0	0
		1:10:00 pM	0	0.01	1.537421267	0
0		1:40:00 pM	0.5	0.05	7.687106336	1.844644234
0.5		14:10	1	0.07	10.76194887	3.689288468
		3:10:00 PM	2	0.07	10.76194887	7.378576936
1		5:10:00 PM	4	0.08	12.29937014	14.75715387
2		9.10 pm	8	0.15	23.06131901	29.51430774
3	14-Mar	1.10 am	12	0.2	30.74842534	44.27146161
4		1.10 pm	24	0.2	30.74842534	88.54292323
6	15-Mar	1.10 pm	48	0.25	38.43553168	177.0858465
8	16-Mar	1.10 pm	72	0.25	38.43553168	265.6287697
19	17-Mar	1.12 pm	96	0.25	38.43553168	354.1716929
24	18-Mar	1.06 pm	120	0.25	38.43553168	442.7146161
	19-Mar	1.10 pm	144	0.25	38.43553168	531.2575394
	20-Mar	1.12 pm	168	0.21	32.28584661	619.8004626
	21-Mar	1.30 pm	192.3	0.21	32.28584661	709.4501724
	22-Mar	1.18 pm	216	0.21	32.28584661	796.8863091
	23-Mar	**2.45 pm**	240.5	0.21	32.28584661	887.2738765
	24-Mar	**4.15 pm**	264	0.21	32.28584661	973.9721555
	25-Mar	**1.50 pm**	288.5	0.21	32.28584661	1064.359723
	26-Mar	**1.10 pm**	312	0.21	32.28584661	1151.058002
	27-Mar	**1.10 pm**	336	0.21	32.28584661	1239.600925
	28-Mar	**1.10 pm**	360	0.21	32.28584661	1328.143848
	29-Mar	**1.07 pm**	384	0.21	32.28584661	1416.686772
	30-Mar	**9.30 am**	403.22	0.21	32.28584661	1487.594896
	31-Mar	**1.13 pm**	432	0.21	32.28584661	1593.772618
	1-Apr	**1.05 pm**	456	0.21	32.28584661	1682.315541
	2-Apr	1.25 pm	480.33	0.21	32.28584661	1772.07593
	3-Apr	1.10 pm	504	0.21	32.28584661	1859.401388
	4-Apr	1.10 pm	528	0.21	32.28584661	1947.944311
	5-Apr	1.30 pm	552.3	0.21	32.28584661	2037.594021
	6-Apr	1.15 pm	586	0.21	32.28584661	2161.923042
	7-Apr	1.15 pm	610	0.21	32.28584661	2250.465965
	8-Apr	1.35 pm	634.5	0.21	32.28584661	2340.853533
	9-Apr	2.34 pm	658.5	0.21	32.28584661	2429.396456
	10-Apr	2.18 pm	682.5	0.21	32.28584661	2517.939379
	11-Apr	1.30 pm	706.5	0.22	33.82326788	2606.482303
	12-Apr	12.45 pm	730.5	0.22	33.82326788	2695.025226
	13-Apr	1.45 pm	754.5	0.23	35.36068914	2783.568149
	14-Apr	1.50 pm	778.5	0.23	35.36068914	2872.111072
	15-Apr	1.25 pm	802	0.23	35.36068914	2958.809351
	16-Apr	1.10 pm	825.7	0.23	35.36068914	3046.245488
	17-Apr	1.10 pm	849.7	0.23	35.36068914	3134.788411
	18-Apr	1.25 pm	874	0.23	35.36068914	3224.438121
	19-Apr	1.10 pm	897.7	0.23	35.36068914	3311.874258
	20-Apr	1.30 pm	922	0.23	35.36068914	3401.523967
	21-Apr	1.30 pm	946	0.23	35.36068914	3490.066891
	22-Apr	1.40 pm	970	0.23	35.36068914	3578.609814
	23-Apr	1.20 pm	993.7	0.23	35.36068914	3666.04595
	24-Apr	11.33 am	1017.7	0.23	35.36068914	3754.588874

	IBM cell		104.1 C			Base brine (4% salinity) +VX12279@0.1%)
	Core 114-2				oil recovery	
			Time,Hr	oil,ml	Base brine	tD
	13-Mar	12:25:00 pM	0	0	0	0
		1:10:00 pM	0	0.001	0.060620891	0
0		1:40:00 pM	0.5	0.001	0.060620891	1.844644234
0.5		14:10	1	0.05	3.031044558	3.689288468
		3:10:00 PM	2	0.05	3.031044558	7.378576936
1		5:10:00 PM	4	0.2	12.12417823	14.75715387
2		9.10 pm	8	0.2	12.12417823	29.51430774
3	14-Mar	1.10 am	12	0.4	24.24835646	44.27146161
4		1.10 pm	24	0.4	24.24835646	88.54292323
6	15-Mar	1.10 pm	48	0.5	30.31044558	177.0858465
8	16-Mar	1.10 pm	72	0.5	30.31044558	265.6287697
19	17-Mar	1.12 pm	96	0.6	36.3725347	354.1716929
24	18-Mar	1.06 pm	120	0.65	39.40357925	442.7146161
	19-Mar	1.10 pm	144	0.65	39.40357925	531.2575394
	20-Mar	1.12 pm	168	0.65	39.40357925	619.8004626
	21-Mar	1.30 pm	192.3	0.75	45.46566837	709.4501724
	22-Mar	1.18 pm	216	0.75	45.46566837	796.8863091
	23-Mar	**2.45 pm**	240.5	0.8	48.49671293	887.2738765
	24-Mar	**4.15 pm**	264	0.8	48.49671293	973.9721555
	25-Mar	**1.50 pm**	288.5	0.8	48.49671293	1064.359723
	26-Mar	**1.10 pm**	312	0.85	51.52775749	1151.058002
	27-Mar	**1.10 pm**	336	0.85	51.52775749	1239.600925
	28-Mar	**1.10 pm**	360	0.85	51.52775749	1328.143848
	29-Mar	**1.07 pm**	384	0.85	51.52775749	1416.686772
	30-Mar	**9.30 am**	403.22	0.85	51.52775749	1487.594896
	31-Mar	**1.13 pm**	432	0.85	51.52775749	1593.772618
	1-Apr	**1.05 pm**	456	0.85	51.52775749	1682.315541
	2-Apr	1.25 pm	480.33	0.85	51.52775749	1772.07593
	3-Apr	1.10 pm	504	0.85	51.52775749	1859.401388
	4-Apr	1.10 pm	528	0.85	51.52775749	1947.944311
	5-Apr	1.30 pm	552.3	0.85	51.52775749	2037.594021
	6-Apr	1.15 pm	586	0.85	51.52775749	2161.923042
	7-Apr	1.15 pm	610	0.85	51.52775749	2250.465965
	8-Apr	1.35 pm	634.5	0.88	53.34638422	2340.853533
	9-Apr	2.34 pm	658.5	0.88	53.34638422	2429.396456
	10-Apr	2.18 pm	682.5	0.88	53.34638422	2517.939379
	11-Apr	1.30 pm	706.5	0.88	53.34638422	2606.482303
	12-Apr	12.45 pm	730.5	0.89	53.95259313	2695.025226
	13-Apr	1.45 pm	754.5	0.9	54.55880205	2783.568149
	14-Apr	1.50 pm	778.5	0.9	54.55880205	2872.111072
	15-Apr	1.25 pm	802	0.9	54.55880205	2958.809351
	16-Apr	1.10 pm	825.7	0.9	54.55880205	3046.245488
	17-Apr	1.10 pm	849.7	0.95	57.5898466	3134.788411
	18-Apr	1.25 pm	874	1	60.62089116	3224.438121
	19-Apr	1.10 pm	897.7	1	60.62089116	3311.874258
	20-Apr	1.30 pm	922	1	60.62089116	3401.523967
	21-Apr	1.30 pm	946	1	60.62089116	3490.066891
	22-Apr	1.40 pm	970	1	60.62089116	3578.609814
	23-Apr	1.20 pm	993.7	1	60.62089116	3666.04595
	24-Apr	11.33 am	1017.7	1.05	63.65193572	3754.588874

Core 149-2		Base brine (4% salinity) +VX12279@0.1%)	
	oil recovery		
oil,ml	Base brine (15% salinity +VX12279 @ 0.1%)	tD	
0	0	0	
0.005	0.418760723	0	
0.01	0.837521445	1.844644234	
0.02	1.67504289	3.689288468	
0.02	1.67504289	7.378576936	
0.08	6.700171561	14.75715387	
0.2	16.7504289	29.51430774	
0.2	16.7504289	44.27146161	
0.2	16.7504289	88.54292323	
0.25	20.93803613	177.0858465	
0.35	29.31325058	265.6287697	
0.35	29.31325058	354.1716929	
0.35	29.31325058	442.7146161	
0.35	29.31325058	531.2575394	
0.35	29.31325058	619.8004626	
0.35	29.31325058	709.4501724	
0.35	29.31325058	796.8863091	
0.35	29.31325058	887.2738765	
0.35	29.31325058	973.9721555	
0.35	29.31325058	1064.359723	
0.35	29.31325058	1151.058002	
0.35	29.31325058	1239.600925	
0.35	29.31325058	1328.143848	
0.35	29.31325058	1416.686772	
0.35	29.31325058	1487.594896	
0.35	29.31325058	1593.772618	
0.35	29.31325058	1682.315541	
0.35	29.31325058	1772.07593	
0.35	29.31325058	1859.401388	
0.35	29.31325058	1947.944311	
0.35	29.31325058	2037.594021	
0.35	29.31325058	2161.923042	
0.35	29.31325058	2250.465965	
0.35	29.31325058	2340.853533	
0.35	29.31325058	2429.396456	
0.35	29.31325058	2517.939379	
0.35	29.31325058	2606.482303	
0.37	30.98829347	2695.025226	
0.37	30.98829347	2783.568149	
0.37	30.98829347	2872.111072	
0.37	30.98829347	2958.809351	
0.37	30.98829347	3046.245488	
0.37	30.98829347	3134.788411	
0.37	30.98829347	3224.438121	
0.37	30.98829347	3311.874258	
0.37	30.98829347	3401.523967	
0.37	30.98829347	3490.066891	
0.37	30.98829347	3578.609814	
0.37	30.98829347	3666.04595	
0.37	30.98829347	3754.588874	

	IBM cell		104.1 C			Base brine (10% salinity) +VX12279 @ 0.2%)	
	Core 149-3				oil recovery		
			Time,Hr	oil,ml	Base brine (10% salinity +VX	tD	
	13-Mar	12:25:00 pM	0	0	0	0	
		1:10:00 pM	0	0	0	0	
0		1:40:00 pM	0.5	0	0	1.844644234	
0.5		14:10	1	0.0001	0.003777424	3.689288468	
		3:10:00 PM	2	0.01	0.377742376	7.378576936	
1		5:10:00 PM	4	0.07	2.644196632	14.75715387	
2		9.10 pm	8	0.15	5.66613564	29.51430774	
3	14-Mar	1.10 am	12	0.3	11.33227128	44.27146161	
4		1.10 pm	24	0.5	18.8871188	88.54292323	
6	15-Mar	1.10 pm	48	0.7	26.44196632	177.0858465	
8	16-Mar	1.10 pm	72	0.7	26.44196632	265.6287697	
19	17-Mar	1.12 pm	96	0.8	30.21939008	354.1716929	
24	18-Mar	1.06 pm	120	0.83	31.35261721	442.7146161	
	19-Mar	1.10 pm	144	0.83	31.35261721	531.2575394	
	20-Mar	1.12 pm	168	0.83	31.35261721	619.8004626	
	21-Mar	1.30 pm	192.3	0.9	33.99681384	709.4501724	
	22-Mar	1.18 pm	216	0.9	33.99681384	796.8863091	
	23-Mar	**2.45 pm**	240.5	0.9	33.99681384	887.2738765	
	24-Mar	**4.15 pm**	264	0.9	33.99681384	973.9721555	
	25-Mar	**1.50 pm**	288.5	0.9	33.99681384	1064.359723	
	26-Mar	**1.10 pm**	312	0.98	37.01875284	1151.058002	
	27-Mar	**1.10 pm**	336	0.99	37.39649522	1239.600925	
	28-Mar	**1.10 pm**	360	0.99	37.39649522	1328.143848	
	29-Mar	**1.07 pm**	384	0.99	37.39649522	1416.686772	
	30-Mar	**9.30 am**	403.22	1	37.7742376	1487.594896	
	31-Mar	**1.13 pm**	432	1	37.7742376	1593.772618	
	1-Apr	**1.05 pm**	456	1	37.7742376	1682.315541	
	2-Apr	1.25 pm	480.33	1	37.7742376	1772.07593	
	3-Apr	1.10 pm	504	1	37.7742376	1859.401388	
	4-Apr	1.10 pm	528	1	37.7742376	1947.944311	
	5-Apr	1.30 pm	552.3	1	37.7742376	2037.594021	
	6-Apr	1.15 pm	586	1	37.7742376	2161.923042	
	7-Apr	1.15 pm	610	1	37.7742376	2250.465965	
	8-Apr	1.35 pm	634.5	1	37.7742376	2340.853533	
	9-Apr	2.34 pm	658.5	1	37.7742376	2429.396456	
	10-Apr	2.18 pm	682.5	1	37.7742376	2517.939379	
	11-Apr	1.30 pm	706.5	1	37.7742376	2606.482303	
	12-Apr	12.45 pm	730.5	1	37.7742376	2695.025226	
	13-Apr	1.45 pm	754.5	1	37.7742376	2783.568149	
	14-Apr	1.50 pm	778.5	1	37.7742376	2872.111072	
	15-Apr	1.25 pm	802	1	37.7742376	2958.809351	
	16-Apr	1.10 pm	825.7	1	37.7742376	3046.245488	
	17-Apr	1.10 pm	849.7	1	37.7742376	3134.788411	
	18-Apr	1.25 pm	874	1.05	39.66294948	3224.438121	
	19-Apr	1.10 pm	897.7	1.05	39.66294948	3311.874258	
	20-Apr	1.30 pm	922	1.05	39.66294948	3401.523967	
	21-Apr	1.30 pm	946	1.05	39.66294948	3490.066891	
	22-Apr	1.40 pm	970	1.05	39.66294948	3578.609814	
	23-Apr	1.20 pm	993.7	1.05	39.66294948	3666.04595	
	24-Apr	11.33 am	1017.7	1.05	39.66294948	3754.588874	

sample	W (g)	H1	H2	H3	H4	H5	H6	H	D1	D2	D3	D4	D5	D6	D	w (after forced saturation)	w(after imbibition)	w (after cleang, dryg &flushg	surfactant
71-2	106.9915	50.33	50.6	50.35	50.47	50.35		50.42	31.8	31.75	31.96	31.92	31.86		31.858	109.5653	108.9837	108.9837	Base Brine (4% salinity) +VX12279 @ 0.2%
71-3	108.7703	50.81	50.68	51.02	50.68	50.6		50.758	31.97	31.98	32.02	32.06	32.01		32.008	110.0397	109.795	109.3372	Base Brine @ 10%
								#DIV/0!							#DIV/0!				
85-1	117.9938	57.33	57.48	57.14	57.28	57.3		57.306	31.86	31.94	32.05	31.59	31.86		31.86	120.468			
85-4	106.2894	50.72	51.41	50.87	51.29	50.75		51.008	31.53	31.99	31.61	31.74	31.88		31.75	106.8246	96.304	96.304	Base Brine (10% salinity) + VX12279 @ 0.2%
								#DIV/0!							#DIV/0!				
114-1	107.7797	50.84	50.79	50.82	50.95	50.74		50.828	31.62	31.81	31.76	31.95	31.7		31.768	108.3223	99.363	99.363	Base Brine (15% salinity) + VX12279@ 0.1%
114-2	108.8743	49.88	49.95	49.95	49.87	49.85		49.9	31.75	31.76	31.78	31.82	31.64		31.75	105.9086	105.253	104.9759	Base Brine (10% salinity) + VX12279 @ 0.1%
								#DIV/0!							#DIV/0!				
149-2	108.2288	50.3	50.03	50.04	50.05	50.13		50.11	31.86	31.92	32.01	31.91	31.9		31.92	109.3546	109.229	109.1628	Base Brine (15% salinity) + VX12279 @0.2%
149-3	103.2314	50.94	50.9	51.05	50.86	50.76		50.902	31.85	31.98	32.06	31.94	32		31.966	105.453	104.9	104.6288	Base Brine (10% salinity) + VX12279@ 0.2%

Appendix IV. Result of CO_2 Core Flooding Experiment.

The initial part of the data:

MM/dd/yyyy HH:mm:ss Measurement Number, n Digital Core Inlet Pressure, Psia Digital Core Inlet Temperature, F Digital Core Outlet Pressure, Psia Digital Core Outlet Temperature, F DAQ Zero, Volts Vacuum Transducer, Psia Low dP Transducer, Psid High dP Transducer, Psid OHaus Mass, grams Cold CO2 Fill Pressure, psi Cold CO2 Fill Flow Rate, ml/min Cold CO2 Fill Volume, ml Hot CO2 Inj. Pressure, psi Hot CO2 Inj. Flow Rate, ml/min Hot CO2 Inj. Volume, ml Hot Oil inj. Pressure, psi Hot Oil inj. Flow Rate, ml/min Hot Oil inj. Volume, ml

11/09/2018 18:14:39 1 13.545380167485607 110.94775390625 14.485152063251633 97.98828125 -0.00063 -0.00038 0.0658 4.52143 78.303 3000.0 -2.222886 8.63226 1435.6 0.0 9.369997 1282.8 0.0 5.044596

11/09/2018 18:14:44 2 13.544218289854168 111.19912109375001 14.470213636561763 98.19833984375 -0.00063 -0.00041 0.06511 4.98848 78.303 3000.0 -1.919584 8.80039 1435.4 0.0 9.369997 1283.0 0.0 5.044596

11/09/2018 18:14:49 3 13.564523484651138 111.41533203125 14.471209531674422 98.35654296875 -0.00064 -0.00041 0.06529 5.23867 78.302 3000.0 -2.348597 8.985398 1435.6 0.0 9.369997 1282.8 0.0 5.044596

11/09/2018 18:14:54 4 13.531902386960969 111.64912109375 14.496947887586003 98.49716796875 -0.00064 -0.0004 0.06502 5.31727 78.303 3000.0 -1.965478 9.1655 1435.6 0.0 9.369997 1283.2 0.0 5.044596

11/09/2018 18:14:59 5 13.50626362056065 111.88291015625 14.483403714053855 98.67119140625 -0.00063 -0.00038 0.06513 5.41382 78.301 3000.6 -2.192955 9.337205 1435.8 0.0 9.369997 1283.0 0.0 5.044596

11/09/2018 18:15:04 6 13.521168850746767 112.09912109375 14.483613958577639 98.79423828125 -0.00064 -0.00038 0.066 5.43728 78.301 3000.0 -2.171105 9.532706 1435.6 0.0 9.369997 1282.8 0.0 5.044596

11/09/2018 18:15:09 7 13.468408540778398 112.36806640625001 14.483436910557609 99.02187500000001 -0.00062 -0.00038 0.06582 5.49258 78.301 3000.0 -2.043299 9.703995 1435.6 0.0 9.369997 1283.0 0.0 5.044596

11/09/2018 18:15:14 8 13.500753000937276 112.58427734375 14.482551670457468 99.16162109375 -0.00064 -0.00041 0.06593 5.49293 78.300 3000.0 -2.354583 9.897151 1435.8 0.0 9.369997 1283.0 0.0 5.044596

11/09/2018 18:15:19 9 13.476397832682164 112.8189453125 14.481622168352322 99.32070312500001 -0.00065 -0.00039 0.06593 5.52605 78.302 3000.0 -1.993414 10.077985 1436.2 0.0 9.369997 1282.8 0.0 5.044596

11/09/2018 18:15:24 10 13.481167063721674 113.03515625 14.485683207311714 99.4947265625 -0.00063 -0.00038 0.06518 5.5631 78.301 3000.0 -2.31268 10.26419 1436.2 0.0 9.369997 1283.0 0.0 5.044596

11/09/2018 18:15:29 11 13.424965382864007 113.26894531250001 14.504793327973497 99.651171875 -0.00064 -0.00039 0.06518 5.57838 78.301 3000.0 -2.129102 10.444725 1436.4 0.0 9.369997 1283.0 0.0 5.044596

11/09/2018 18:15:34 12 13.4725138417428 113.5203125 14.479409068101972 99.84541015625 -0.00063 -0.0004 0.06549 5.59303 78.303 3000.0 -2.288735 10.63527 1436.4 0.0 9.369997 1283.0 0.0 5.044596

11/09/2018 18:15:39 13 13.457110664000357 113.75498046875 14.499094594828842 99.9833984375 -0.00064 -0.00039 0.06571 5.61639 78.301 3000.6 -2.173001 10.814175 1436.6 0.0 9.369997 1283.2 0.0 5.044596

11/09/2018 18:15:44 14 13.471374095113868 113.9703125 14.494956097360689 100.12314453125 -0.00064 -0.00038 0.06544 5.6186 78.300 3000.0 -2.208918 11.009126 1436.2 0.0 9.369997 1283.2 0.0 5.044596

11/09/2018 18:15:49 15 13.468076575740843 114.16806640625 14.492023739528971 100.2998046875 -0.00063 -0.0004 0.06547 5.57727 78.298 3000.0 -2.194951 11.187499 1436.4 0.0 9.369997 1283.2 0.0 5.044596

11/09/2018 18:15:54 16 13.494445665223775 114.40185546875 14.48078119025719 100.45625 -0.00064 -0.00042 0.06582 5.58994 78.300 3000.0 -2.209118 11.382551 1436.4 0.0 9.369997 1283.2 0.0 5.044596

11/09/2018 18:15:59 17 13.435466543551925 114.63564453125001 14.50840068138157 100.63027343750001 -0.00063 -0.0004 0.06607 5.58393 78.302 3000.0 -1.92557 11.519635 1436.6 0.0 9.369997 1283.4 0.0 5.044596

11/09/2018 18:16:04 18 13.425208823891548 114.86943359375 14.483602893076386 100.804296875 -0.00064 -0.00042 0.06631 5.58662 78.300 3000.0 -2.400478 11.708468 1436.6 0.0 9.369997 1283.6 0.0 5.044596

11/09/2018 18:16:09 19 13.462167598072408 115.12343750000001 14.480781190257186 100.96337890625 -0.00063 -0.00038 0.06564 5.6124 78.300 3000.0 -2.109148 11.900775 1436.8 0.0 9.369997 1283.4 0.0 5.044596

11/09/2018 18:16:14 20 13.422077287037302 115.3203125 14.490352848839956 101.10224609375 -0.00064 -0.0004 0.06573 5.63187 78.296 3000.6 -2.067244 12.066843 1436.8 0.0 9.369997 1283.6 0.0 5.044596

11/09/2018 18:16:19 21 13.404461009044507 115.53740234375 14.47021363656176
101.26044921875 -0.00064 -0.00042 0.06573 5.63259 78.300
3000.0 -2.320661 12.259118 1437.0 0.0 9.369997 1283.6 0.0
5.044596

11/09/2018 18:16:24 22 13.432722299241487 115.77119140625 14.49700321509226
101.43623046875 -0.00064 -0.00039 0.06533 5.6403 78.299 3000.0
-1.919584 12.43473 1437.0 0.0 9.369997 1283.4 0.0 5.044596

11/09/2018 18:16:29 23 13.403476179433099 116.005859375 14.493528647699208
101.61025390625001 -0.00062 -0.00038 0.06573 5.60061 78.303
3000.0 -2.334629 12.618391 1437.2 0.0 9.369997 1283.4 0.0
5.044596

11/09/2018 18:16:34 24 13.410801541261762 116.202734375 14.497600752159855
101.74912109375 -0.00063 -0.00038 0.06551 5.63203 78.298
3000.0 -1.957497 12.798261 1436.8 0.0 9.369997 1283.8 0.0
5.044596

11/09/2018 18:16:39 25 13.391470110574947 116.43828125 14.506054795116196
101.908203125 -0.00063 -0.00037 0.0658 5.62824 78.299 3000.0 -
2.268781 12.974955 1437.4 0.0 9.369997 1283.8 0.0 5.044596

11/09/2018 18:16:44 26 13.363308409889232 116.67294921875 14.499614673387674
102.06376953125 -0.00063 -0.0004 0.06489 5.60773 78.302 3000.0
-2.073231 13.160744 1437.0 0.0 9.369997 1283.8 0.0 5.044596

……………………………………………………………………………………………… CONTD.

Appendix V. Typical Script of 'STARS' CMG Numerical Simulation.

15-15-15 5 years at 50000 cfm injection rate;

```
** ***************************************************************************
** Template  (stdrm012.dat): Gravity Drainage in a Dual Permeability Grid  **
** ***************************************************************************
**
*****************************************************************************
** **
** FILE :  STDRM012.DAT                                          **
** **
** MODEL:  DUAL HORIZONTAL WELL SAGD MODEL              FIELD UNITS          **
** 1/2 PATTERN DUAL PERMEABILITY FRACTURED NETWORK  5X1X10 CARTESIAN GRID   **
** MODIFIED PROPERTIES VERSION OF SPE COMPARATIVE SOLUTION PROJECT        **
** **
** USAGE:  APPLICATION OF DK FOR NATURALLY FRACTURED GRAVITY DRAINAGE RESERVOIRS    **
** **
**
*****************************************************************************
**
*****************************************************************************
** **
** This is the STARS data set for Lee's modified "Fourth SPE              **
** Comparative Solution Project - a Comparison of Steam Injection          **
** Simulators", paper SPE 13510, presented at the eighth SPE symposium       **
** on reservoir simulation at Dallas, Texas, Feb. 10-13, 1985. Lee's         **
** paper is SPE 16009, 9th SPE symposium on reservoir simulation, San        **
** Antonio, Texas, Feb. 1987.                                    **
** **
** The problem is a gravity drainage 2 horizontal wells, with water and      **
** a dead oil.  A two-dimensional cross-sectional study is required.        **
** **
** Features:                                       **
** **
** 1)  Two-dimensional cross-sectional X-Z coordinates.                    **
** **
** 2)  Distinct permeability layering.                             **
** **
** 3)  Black-oil type treatment of fluids. Oil density has                **
** been increased by Lee to make heavier than water.                  **
** **
** 4)  Oil viscosity has been modified to heavy oil/bitumen.  Sharp         **
** changes occur at the steam front (33500 cp at 100 F to 4.23 cp        **
** at 450 F).                                       **
** **
** 5)  Automatic initial vertical equilibrium calculation.                **
```

```
** **
** 6)  Multi-layer well with additional injection and production            **
** operating constraints.                                      **
** **
** 7)  A dual permeability approach to modelling naturally                 **
** fractured reservoirs is employed.                              **
** **
**
*************************************************************************************
** =============  INPUT/OUTPUT CONTROL  =====================
** 2018-07-06, 10:58:23 PM, barco.yolo
RESULTS SIMULATOR STARS 201410


*INTERRUPT *STOP

*TITLE1 'Well #12071 '
*TITLE2 'Simple Gravity Drainage Process'
**TITLE3 'Natural Fractures Modelled with the Dual Permeability Option'
**RESTART 1735
**RESTART 15600
*INUNIT *Field  *EXCEPT  2 1  EXCEPT 5 2 ** deg C instead of deg F


*OUTPRN *GRID *PRES *SW *SO *SG *TEMP *Y *OBHLOSS
*OUTPRN *WELL *ALL
*OUTPRN *ITER *TSS
*WPRN GRID 400
*WPRN *ITER 400
*WPRN SECTOR 400
*WRST 300
WSRF SECTOR TIME
*PRNTORIEN 2 0
OUTSRF GRID PRES SG SO SW
*DIM *MDLU 6000000
RESULTS XOFFSET     1414311.8800
RESULTS YOFFSET      732395.1900
RESULTS ROTATION          0.0000  **$  (DEGREES)
RESULTS AXES-DIRECTIONS 1.0 -1.0 1.0
**$ ***************************************************************************
**$ Definition of fundamental cartesian grid
**$ ***************************************************************************
*****Modified in 1-D  GRID VARI 10 10 1


GRID VARI 30 30 3
KDIR DOWN
DI IVAR
```

```
 30*355
DJ JVAR
 30*286
DK CON
 20

***** modified

**DUALPERM              **   Fracture spacing mimics Lee's sigma=3 value
**DIFRAC *CON 1.633       **   Reservoir has vertical fractures only
**DJFRAC EQUALSI
**DKFRAC *CON 0

POR MATRIX KVAR
 0.07  0.01  0.05
**POR FRACTURE KVAR
**0.006 0.002 0.002
PERMI MATRIX KVAR
 0.01 15 116
***PERMI *FRACTURE
**KVAR 0.031 0.031 0.0128   ***CON 3617

PERMJ MATRIX KVAR
 0.01 15 116


PERMK MATRIX KVAR *** times 0.1 from PERM I
 0.01 15 116

***PERMK *FRACTURE **CON 3617
**KVAR 0.031 0.031 0.0128
**  0 = pinched block, 1 = active block
PINCHOUTARRAY CON          1
**SECTORARRAY 'AREA' MATRIX  ALL
**110*0 5*1 5*0 5*1 5*0 5*1 5*0 5*1 5*0 5*1 5*0 5*1 99*0 5*1 5*0 5*1 5*0

** 5*1 5*0 5*1 1*0
SECTOR 'FIELD 12071'
1:30 1:30 1:3
**NULL *MATRIX CON          1
*END-GRID
ROCKTYPE 1

** Intrinsic formation/matrix properties
*CPOR 5E-5
*ROCKCP 35
*THCONR 24
*THCONW 24
```

```
*THCONO 24
*THCONG 24

*HLOSSPROP *OVERBUR 35 24 *UNDERBUR 35 24



**  =============  FLUID DEFINITIONS  =====================


** Reference conditions
*MODEL 4 4 4     ** North Sea light oil

*COMPNAME   'WATER'   'CHEM'    'OIL'    'GAS'
**        -------  -------    -----    --------

CMM        18.02     706.32      585.01  44.01   **  585.01 0.018Kg/gmole or 18.02 lb/lbmole 58N C6-10
#15845 44.01g/mol of CO2
MOLDEN     0.055     0.0014     0.00049  0.023        **1/CMM
CP         0        0          1.1e-5    1e-6
CT1       2.33e-4  2.33e-4     3.8e-4     1e-4    ** #15845 11.35
PCRIT      3200    632         657       1071          ** #12160
TCRIT       374       98.9        500      31.1     ** #12160 449 R
CPL1         0      300        300        8.815

**CMM        0.018     0.43      0.1     0.028
**MOLDEN      1566     65.56     204.1     730
**CP         3e-6      3e-6     1e-6     1e-6
**CT1       2.33e-4  2.33e-4    1e-4     1e-4
**PCRIT      3200      632       453     492.4
**TCRIT       374      134       175      -147

**CPL1         0      0.2417   0.2417   0.008815
*RANGECHECK *OFF
SOLID_DEN 'CHEM' 0.063 0 0     **lb/gt3  cp, ct 1.0117
**SOLID_DEN 'CHEM' 28190.8 0 0
*RANGECHECK *ON
*SOLID_CP 'CHEM' 0.016112889 0    ** (17 J/gmole-C) * ( 1 Btu / 1055.056 J )
**SOLID_CP 'CHEM' 0.016112889 0    ** (17 J/gmole-C) * ( 1 Btu / 1055.056 J )

*WATPHASE
*VISCTABLE
**Temp TDS:286,738 ppm

     15     0  2.46   1.87    2.44
     20     0  2.16   1.726   2.24
     30     0  1.71   1.704     2.04
     40     0  1.38   1.229     1.98
```

```
    50     0  1.14   1.022     1.76
    60     0  0.95   0.933     1.53
    70     0  0.80    0.768    1.23
    80     0  0.69   0.665     1.13
    90     0  0.60   0.571     0.94
    100    0  0.53   0.477     0.76
    110    0  0.47   0.393     0.76
    120    0  0.42   0.343 0.76
    130    0  0.38   0.319 0.76
    330    0  0.18   0.119 0.46

*Xnacl 0.26
*OILPHASE
*VISCTABLE
**Temp
    15     2.46   2.46   1.87    2.44
    20     2.16   2.16   1.726   2.24
    30     1.71   1.71   1.704     2.04
    40     1.38   1.38   1.229     1.98
    50     1.14   1.14   1.022     1.76
    60     0.95   0.95   0.933     1.53
    70     0.80   0.80    0.768    1.23
    80     0.69   0.69   0.665     1.13
    90     0.60   0.60   0.571     0.94
    100    0.53   0.53   0.477     0.76
    110    0.47   0.47   0.393     0.76
    120    0.42   0.42   0.343 0.76
    130    0.38   0.38   0.319 0.76
    330    0.018  0.18   0.119 0.46
*LIQPHASE


*PRSR 1550
*TEMR 104.44
*PSURF 14.7
*TSURF 23
**SURFLASH KVALUE

*GASLIQKV         ** The following are gas-liquid K values

*KVTABLIM  580 12000  5 300

*KVTABLE 'WATER'   ** Want no water in gas phase (override default)
8*0
8*0

*KVTABLE 'GAS'
1.733  1.27   1.049  0.918  0.785  0.757  0.705  0.685
```

```
3.895  2.944  2.437  2.132  1.825  1.759  1.639  1.592

*LIQLIQKV   ** The following are the liquid-liquid K values at 5 concentrations

*KVTABLIM  3000 6000  5 100
** kvkeycomp 'CHEM' global 0 0.008
kvkeycomp 'CHEM' M 0 0.008

*KVTABLE 'WATER'        ** Each component has a P-T dependent table at
  *KEYCOMP              ** the following values of z(CHEM):
    2*0.
    2*0.              **  0.0  0.002  0.004  0.006  0.008
  *KEYCOMP
    2*7E-4
    2*7E-4
  *KEYCOMP
    2*0.0037
    2*0.0037
  *KEYCOMP
    2*0.0125
    2*0.0125

  *KEYCOMP
    2*0.0398
    2*0.0398

*KVTABLE 'CHEM'
  *KEYCOMP
    2*0.1
    2*0.1
  *KEYCOMP
    2*0.1458
    2*0.1458
  *KEYCOMP
    2*0.1741
    2*0.1741
  *KEYCOMP
    2*0.2204
    2*0.2204
  *KEYCOMP
    2*0.3025
    2*0.3025

*KVTABLE 'OIL'
  *KEYCOMP
    2*1E-4
    2*1E-4
  *KEYCOMP
```

```
    2*0.0314
    2*0.0314
  *KEYCOMP
    2*0.1214
    2*0.1214
  *KEYCOMP
    2*0.259
    2*0.259
  *KEYCOMP
    2*0.433
    2*0.433
*KVTABLE 'GAS'
  *KEYCOMP
    2*1E-4
    2*1E-4
  *KEYCOMP
    2*0.0314
    2*0.0314
  *KEYCOMP
    2*0.1214
    2*0.1214
  *KEYCOMP
    2*0.259
    2*0.259
  *KEYCOMP
    2*0.433
    2*0.433


** Since component CHEM's w/o K value is less than 1, the default *SURFLASH
** assumes all CHEM's SR2 reporting is in the oil phase.  Force CHEM's
** surface phase to be water to match the injection.
SURFLASH W W O  G

**  ==============  ROCK-FLUID PROPERTIES  ======================


*ROCKFLUID

*RPT 1    **  -----------  MATRIX  ------------
**  Interpolation between 2 sets:  high versus low IFT situations.

*INTCOMP 'CHEM' *OIL
*INTLIN   ** Linear interpolation of X(surfactant)

*IFTTABLE   ** Surfactant chosen to work best at initial reservoir T
```

```
*TEMP 5       ** 5 deg C Table

**      oil mole frac     IFT
**      -------------    --------
          0.           30
          0.0005        3
          0.001        0.3
          0.002        0.03
          0.003        0.003
          0.004        0.003

*TEMP 90      ** 95 deg C Table

**      oil mole frac     IFT
**      -------------    --------
          0.           10
          0.0005        1
          0.001        0.1
          0.002        0.01
          0.003        0.001
          0.004        0.001


**  Set #1:  High IFT, corresponding to no surfactant
**  ------------------------------------------------

*KRINTRP 1
OILWET

**DTRAPW -4
**DTRAPN -4.222  ** Critical cap num for detrapping to begin

DTRAPW -7.22185
DTRAPN -7.22185
*SWT   **  Water-oil relative permeabilities

**   Sw       Krw      Krow
**  -----    -------    -------
   0.12      0.0       0.8
   0.3      0.025     0.625
   0.4      0.1       0.2
   0.5      0.225     0.125
   0.6      0.4       0.019
   0.7      0.625     0.00425
   0.87      0.9       0.0
** Sor=0.62 based on experiments

*SLT   **  Liquid-gas relative permeabilities
```

```
**   Sl        Krg      Krog
**  ----      -------    ------
    0.21      0.784     0.0
   0.32      0.448     0.01
   0.4       0.288     0.024
   0.472     0.184     0.052
   0.58      0.086     0.152
   0.68      0.024     0.272
   0.832     0.006     0.448
   0.872     0.0       0.9


**  Set #2:  Low IFT, corresponding to high surfactant concentration
**  ------------------------------------------------------------------

*KRINTRP 2
WATWET
DTRAPW -0.63827
DTRAPN -2.92082
***DTRAPW -1.68
***DTRAPN -2.222  ** Critical cap num for complete detrapping

*SWT   **  Water-oil relative permeabilities

**   Sw        Krw      Krow
**  -----     -------    -------
   0.0       0.0      1.
   0.1       0.1      0.9
   0.2       0.2      0.8
   0.3       0.3      0.7
   0.4       0.4      0.6
   0.5       0.5      0.5
   0.6       0.6      0.4
   0.7       0.7      0.3
   0.8       0.8      0.2
   0.9       0.9      0.1
   1.        1.0      0.

*SLT   **  Liquid-gas relative permeabilities

**   Sl        Krg      Krog
**  ----      -------    ------
   0.0       1.       0.
   0.1       0.9      0.1
   0.2       0.8      0.2
   0.3       0.7      0.3
   0.4       0.6      0.4
```

```
   0.5       0.5      0.5
   0.6       0.4      0.6
   0.7       0.3      0.7
   0.8       0.2      0.8
   0.9       0.1      0.9
   1.        0.       1.


**  Adsorption Data
**  ---------------

*ADSCOMP 'CHEM' *WATER   ** Reversible adsorption of aqueous surfactant
*ADSLANG *TEMP      ** Langmuir isotherms at 2 tempertures
  96  20 0 1000
 105   22 0.2 1001
*ADMAXT .02   ** No flow modications from adsorption



*RPT 2    **  -----------  FRACTURE  ------------

*SWT      **  Water-oil relative permeabilities

**   Sw       Krw       Krow
**  ----      ------     ------
   0.0       0.0        1.0
   1.0       1.0        0.0

*SLT     **  Liquid-gas relative permeabilities

**   Sl       Krg       Krog
**  ----      ------     ------
   0.0       1.0         0.0
   1.0       0.0         1.0

**   Assign rel perm sets




**  =============  INITIAL CONDITIONS  =====================


*INITIAL
VERTICAL OFF

** Fractures in layer 5 will have initial pressure of 150 psi
```

```
** Pressure in other layers (matrix and fracture) will be adjusted
** according to gravity

**VERTICAL *DEPTH_AVE
**REFPRES 150
*REFBLOCK 1 1 1
DWOC      9926
*PRES CON 2087


SW *MATRIX   *CON
0.38

**MOD
**1:10 1:10 1:1 * 0.40


**SW *FRACTURE *KVAR
**0.38 0.38 0.487
**MOD
**1:10 1:10 1:1 * 0.50



*TEMP *MATRIX   *CON 95
**TEMP *FRACTURE *CON 95
MFRAC_OIL 'OIL' *MATRIX CON       0.538
MFRAC_OIL 'GAS' *MATRIX CON       0.462


**  =============  NUMERICAL CONTROL  =====================


*NUMERICAL   ** All these can be defaulted.  The definitions
          ** here match the previous data.

NEWTONCYC 10
SDEGREE 1
SORDER *RCMRB
MAXSTEPS 2000000
MAXPRES 145000000


UPSTREAM *KLEVEL
NORM PRESS 290 SATUR 0.4 TEMP 150 Y 0.55 X 0.55 ZO 0.1 ZNCG 3 ZAQ 0.1
**CONVERGE PRESS 1.0 SATUR 0.05 TEMP 0.5 Y 0.05 X 0.05

**MATBALTOL 1
```

```
**NORM     *PRESS 150  *ZO .1    *TEMP 50  *ZNCG .1    *ZAQ .1
*****************************
RUN

DATE 2018 8 31
well 1 'Injector' VERT 5 5
well 2 'W-12071'  VERT 5 5
DTMAX            5
DTWELL           0.00001
INJECTOR UNWEIGHT 'Injector'
TINJW 23
PINJW 8000
INCOMP  GAS  0.0  0.0  0.0  1.0
OPERATE  MAX  BHP  8000  CONT REPEAT
OPERATE  MAX  STG  50000  CONT

**$ UBA     ff  Status  Connection
**$ perf geometric data: UBA, block entry(x,y,z) block exit(x,y,z), length
**        rad  geofac  wfrac  skin

***** modified 1:3 to 1:1 ***** you only have 1 layer.
GEOMETRY  K  0.274 0.949  1  0.0
perfv geo 'Injector'
           **   k wi
            1:3  1.0

**$

PRODUCER 'W-12071'
OPERATE  MIN  BHP  400  CONT REPEAT
OPERATE  MAX  STO  50000  CONT REPEAT
**$ UBA     ff  Status  Connection
**$ perf geometric data: UBA, block entry(x,y,z) block exit(x,y,z), length
**        rad  geofac  wfrac  skin

******* modified GEOMETRY  K  0.486 (rw)  0.249(geofac)  1.0  0.0
GEOMETRY  K  0.274 0.949  1  0.0
    perfv geo 'W-12071'
           **   k wi
            1:3  1.0


**NCUTS 30
```

```
OPEN 'Injector'
SHUTIN 'W-12071'

*****modified
DATE 2018    9    15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2018   9    30
SHUTIN 'Injector'
OPEN 'W-12071'


DATE 2018   10   15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2018   10   30
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2018    11   15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2018   11   30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2018   12   15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2018   12   30
SHUTIN 'Injector'
OPEN 'W-12071'

** 2019
DATE 2019   1   15
  **TINJW 95
                        ** Start on BHP
                              ** 0.2PV/2733400/13667000   ** Maximum water rate
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2019    1   30
SHUTIN 'Injector'
SHUTIN 'W-12071'
```

```
DATE 2019   2    15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2019   2    30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2019     3      15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2019    3     30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2019   4    15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2019    4     30
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2019    5     15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2019   5     30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2019   6   15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2019    6   30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2019      7     15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2019    7    30
SHUTIN 'Injector'
SHUTIN 'W-12071'
```

```
DATE 2019   8    15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2019   8    30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2019   9    15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2019    9     30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2019     10   15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2019   10     30
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2019    11    15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2019   11    30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2019    12    15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2019    12    30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2020   1     15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2020   1   30
SHUTIN 'Injector'
SHUTIN 'W-12071'
```

```
DATE 2020    2    15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2020     2     30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2020    3    15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2020    3    30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2020   4    15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2020   4   30
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2020    5     15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2020     5     30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2020   6     15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2020    6     30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2020   7     15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2020   7    30
SHUTIN 'Injector'
SHUTIN 'W-12071'
```

```
DATE 2020    8    15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2020   8     30
OPEN 'Injector'
SHUTIN 'W-12071'


DATE 2020    9    15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2020   9    30
SHUTIN 'Injector'
OPEN 'W-12071'


DATE 2020   10    15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2020   10   30
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2020    11   15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2020   11   30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2020   12   15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2020   12   30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2021   1   15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2021    1   30
```

```
SHUTIN 'Injector'
SHUTIN 'W-12071'


DATE 2021   2    1
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2021     2      15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2021    2     30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2021   3    15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2021    3     30
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2021    4     15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2021   4     30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2021   5   15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2021    5   30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2021      6     15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2021    6    30
SHUTIN 'Injector'
SHUTIN 'W-12071'
```

```
DATE 2021   7    15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2021   7    30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2021   8    15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2021    8     30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2021     9   15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2021   9     30
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2021    10    15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2021   11    30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2021    12    15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2021    12    30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2022   1     15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2022   1   30
SHUTIN 'Injector'
SHUTIN 'W-12071'
```

```
DATE 2022    2    15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2022     2     30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2022    3    15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2022    3    30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2022   4    15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2022   4   30
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2022    5     15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2022     5     30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2022   6     15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2022    6     30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2022   7     15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2022   7    30
SHUTIN 'Injector'
SHUTIN 'W-12071'
```

```
DATE 2022    8    15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2022   8     30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2022   9    15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2022    9    30
SHUTIN 'Injector'
OPEN 'W-12071'


DATE 2022    10    15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2022    10    30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2022   11    15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2022   11   30
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2022    12      15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2022     12     30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2023   1     15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2023    1      30
SHUTIN 'Injector'
OPEN 'W-12071'
```

```
DATE 2023   2     15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2023   2    30
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2023    3     15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2023   3     30
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2023   4    15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2023    4    30
SHUTIN 'Injector'
OPEN 'W-12071'


DATE 2023    5    15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2023    5    30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2023   6    15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2023   6   30
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2023    7      15
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2023     7     30
OPEN 'Injector'
```

```
SHUTIN 'W-12071'

DATE 2023   8     15
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2023    8      30
SHUTIN 'Injector'
OPEN 'W-12071'

DATE 2023   9     15
OPEN 'Injector'
SHUTIN 'W-12071'

DATE 2023   9    30
SHUTIN 'Injector'
SHUTIN 'W-12071'

DATE 2023    10    15
SHUTIN 'Injector'
OPEN 'W-12071'

STOP
```

Appendix VI. Graphs of the Input PVT Data

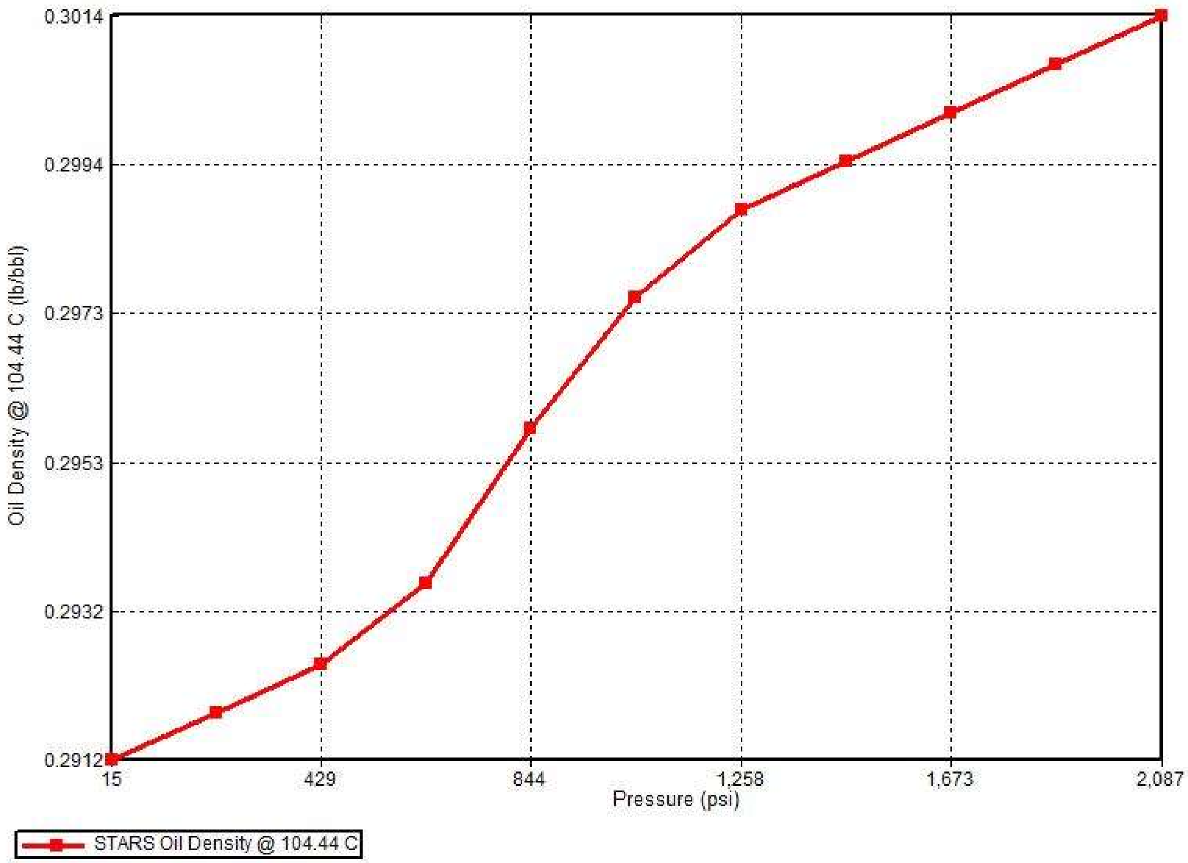

Fig. 55. Pressure (psi) versus Oil density (cp) at 104.44 °C

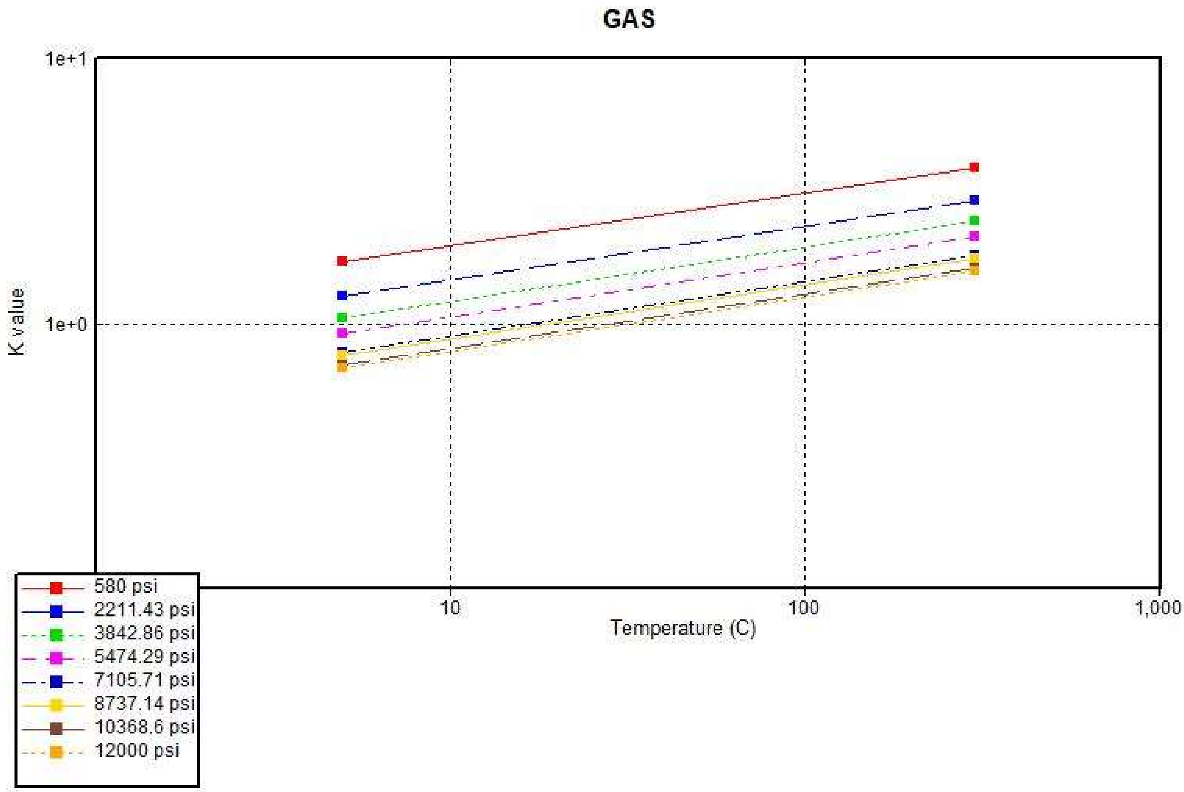

Fig. 56. Temperature versus K[(gas/liq)= (gas mole fraction)/(water mole fraction)] at constant pressures

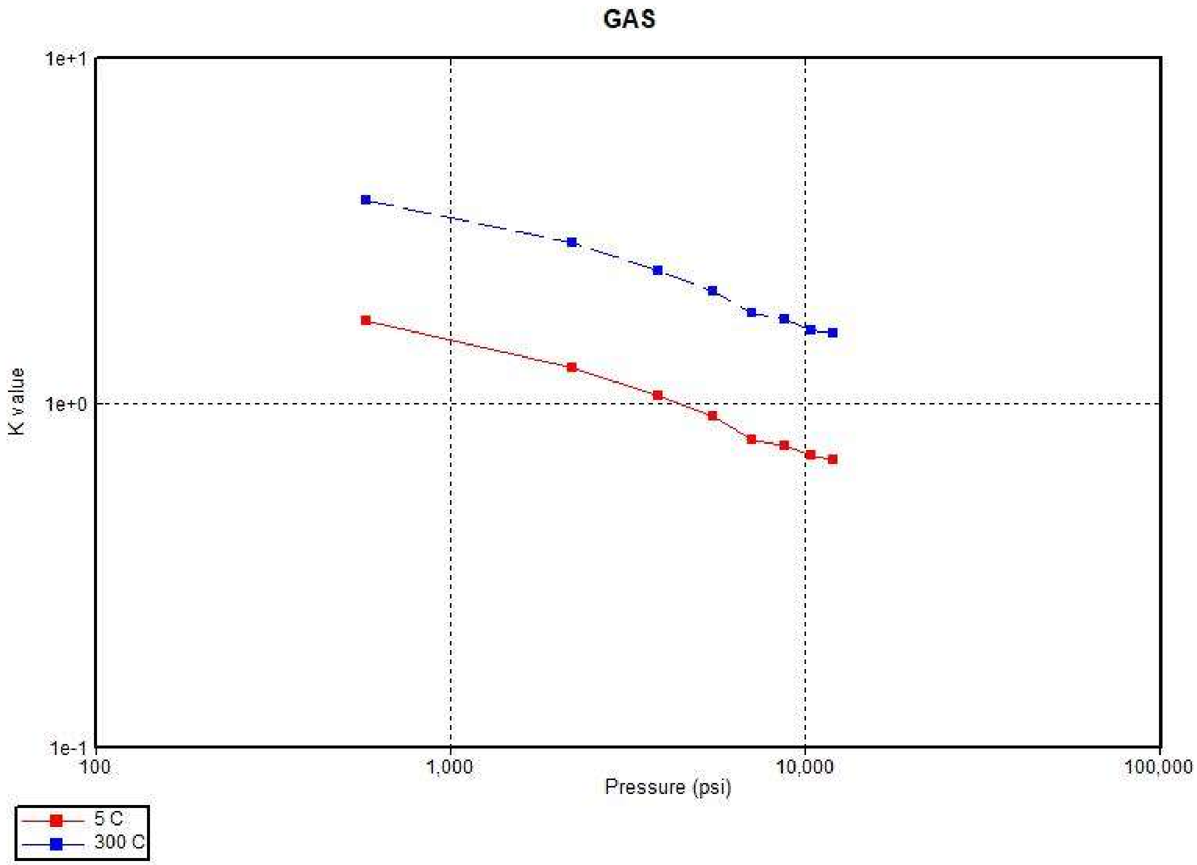

Fig. 57. Pressure versus K[(gas/liq) =(gas mole fraction)/(water mole fraction)] at constant temperatures

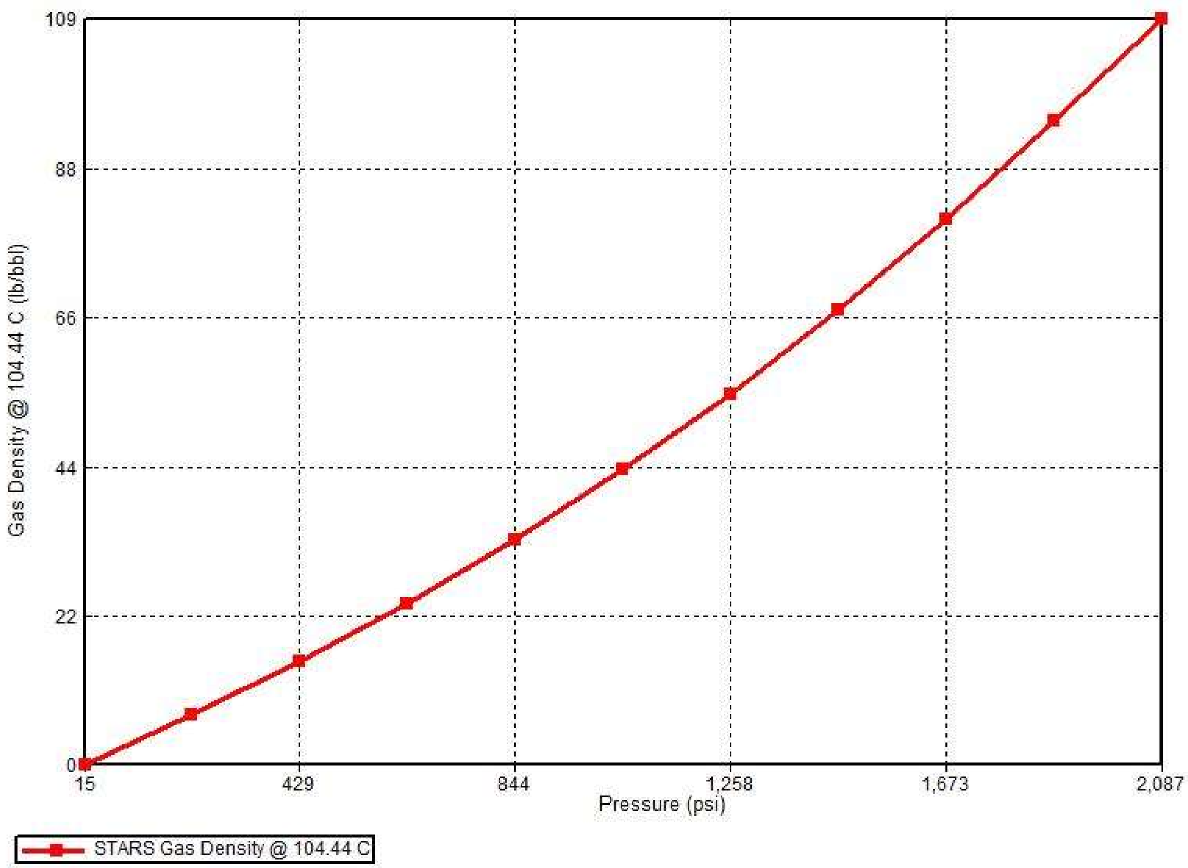

Fig. 58. Pressure versus Gas density at 104.44 °C

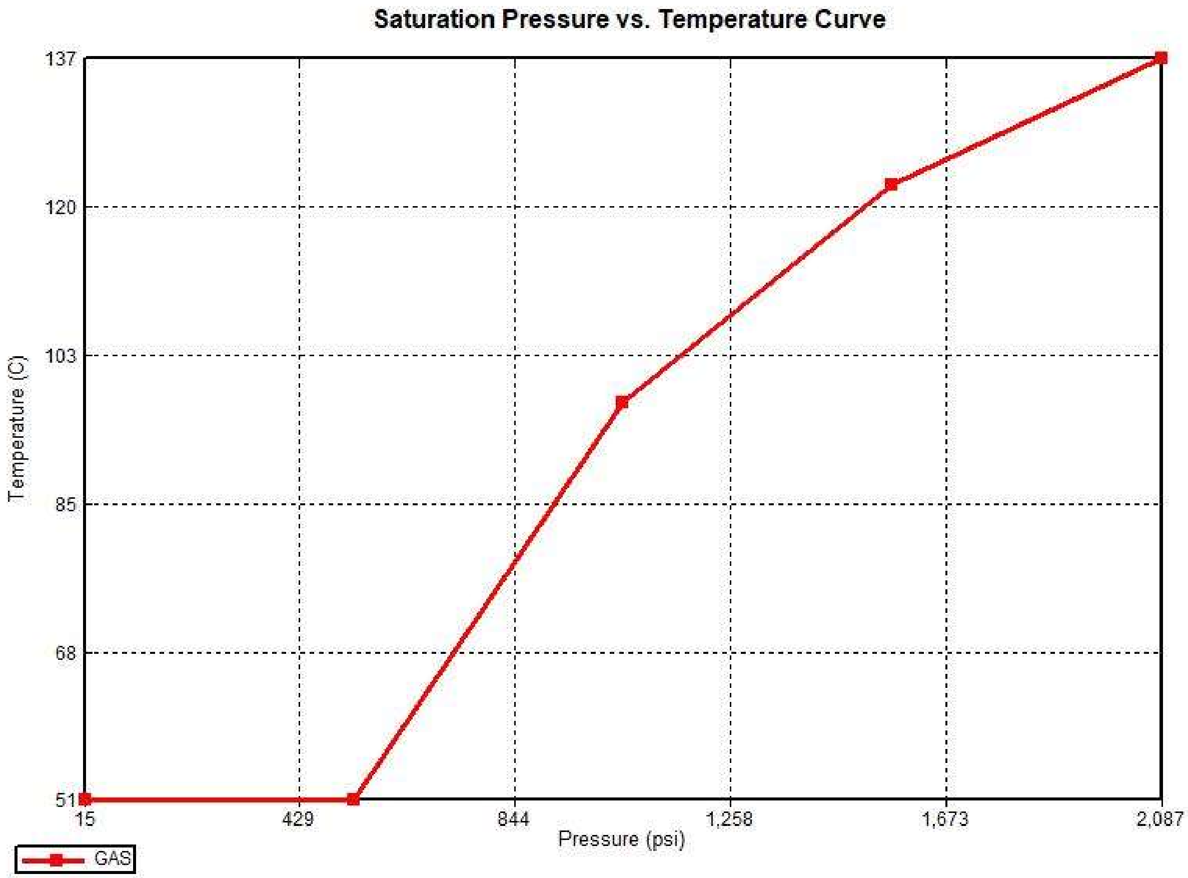

Fig. 59. Saturation Pressure versus Temperature

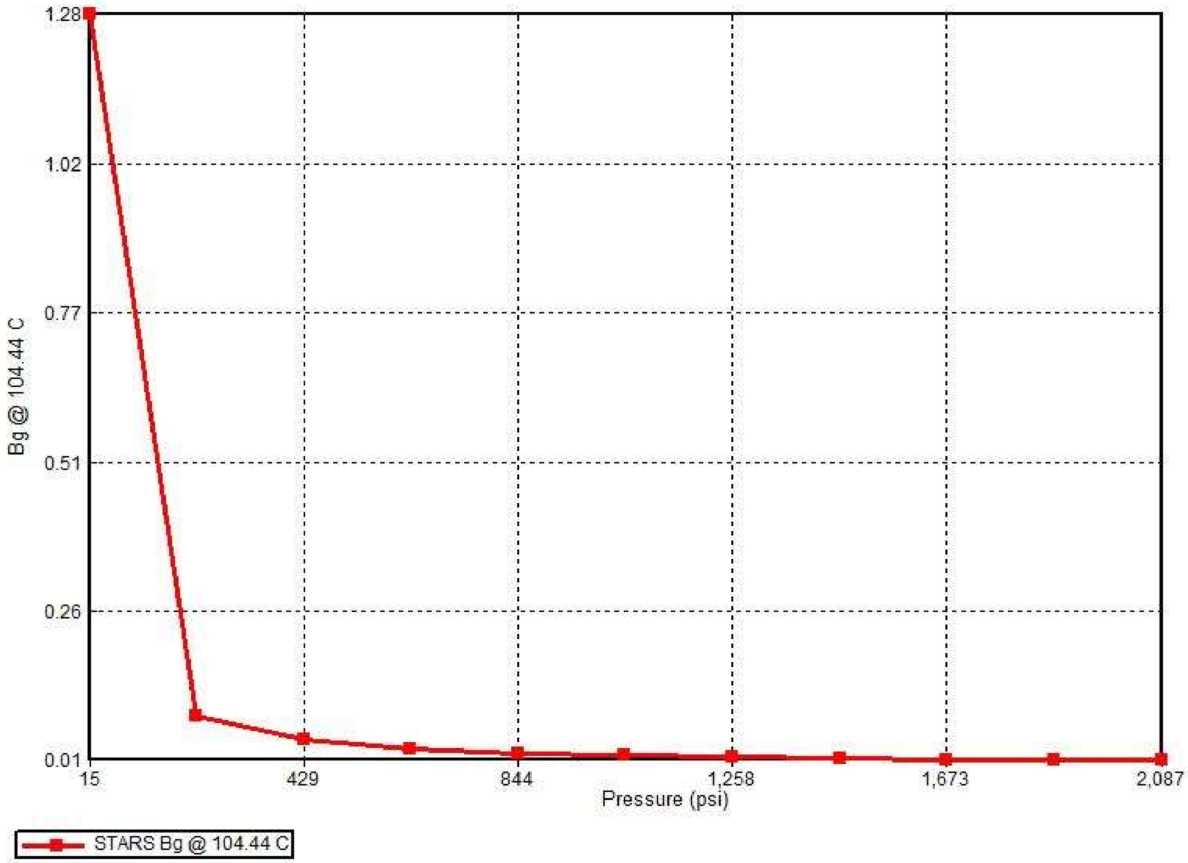

Fig. 60. Pressure versus Bg (Gas formation volume factor, rb/stb) at 104.44 ^{o}C

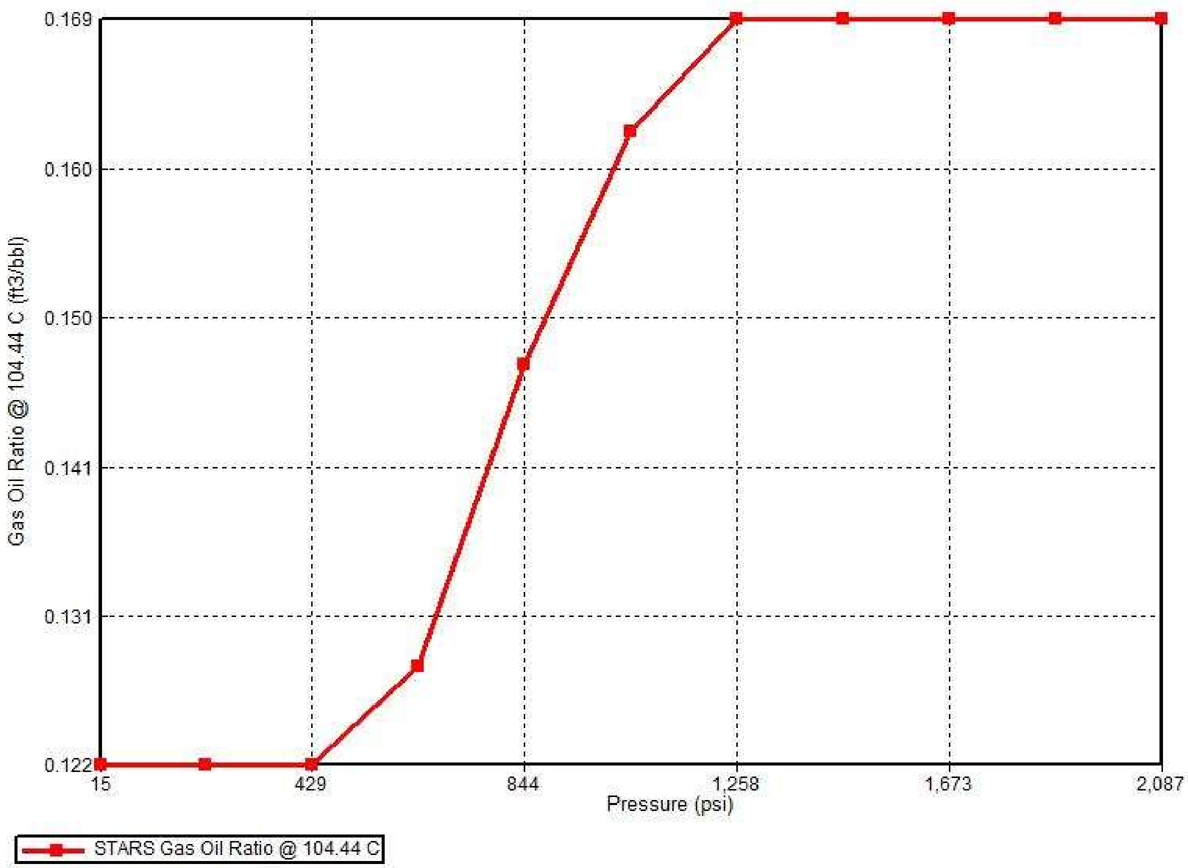

Fig. 61. Pressure versus Gas Oil Ratio at 104.44 °C

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